Activity Report Nancy - Grand Est 2016

Edition: 2017-06-08

List of Inria's Research Teams

Project-Team ALICE

Geometry and Lighting

IN COLLABORATION WITH: Laboratoire lorrain de recherche en informatique et ses applications (LORIA)

IN PARTNERSHIP WITH:
CNRS

Université de Lorraine

RESEARCH CENTER
Nancy - Grand Est

THEME
Interaction and visualization

Table of contents

Project-Team ALICE

Creation of the Project-Team: 2006 January 09

Keywords:

Computer Science and Digital Science:

5.5.1. - Geometrical modeling
5.5.2. - Rendering
6.2.1. - Numerical analysis of PDE and ODE
6.2.8. - Computational geometry and meshes
7.2. - Discrete mathematics, combinatorics
7.5. - Geometry, Topology

Other Research Topics and Application Domains:

3.3.1. - Earth and subsoil
5.1. - Factory of the future
5.7. - 3D printing
9.2.2. - Cinema, Television
9.2.3. - Video games
9.4.1. - Computer science
9.4.2. - Mathematics
9.4.3. - Physics

1. Members

Research Scientists

Bruno Lévy [Team leader, Inria, Senior Researcher, HDR]
Laurent Alonso [Inria, Researcher]
Samuel Hornus [Inria, Researcher]
Sylvain Lefebvre [Inria, Senior Researcher, HDR]
Jonas Martinez Bayona [Inria, Researcher]
Jean-Claude Paul [Inria, Senior Researcher, until Feb 2016, HDR]
Nicolas Ray [Inria, Researcher]

Faculty Members

Dobrina Boltcheva [Univ. Lorraine, Associate Professor]
Dmitry Sokolov [Univ. Lorraine, Associate Professor, HDR]
Cédric Zanni [Univ. Lorraine, Associate Professor]
Guillaume Caumon [Univ. Lorraine, Professor]

Technical Staff

Yamil Salim Perchy [Inria]
Tim-Christopher Reiner [Inria, until Feb 2016]

PhD Students

Jérémie Dumas [Inria, granted by ERC]
Jean Hergel [Inria, granted by ERC]
Maxence Reberol [Inria]
Julien Renaudeau [Gocad, granted by CIFRE]
Arnaud Botella [ASGA/Gocad Consortium, until Sep 2016]

Post-Doctoral Fellows

Shuo Jin [Inria, from Jul 2016]
Haichuan Song [Inria]

Administrative Assistants

Laurence Félicité [Univ. Lorraine, Assistant]
Virginie Priester [CNRS, Assistant, from Apr 2016]
Céline Simon [Inria, Assistant]

Others

Weikai Chen [University of Hong Kong, PhD Student, from Jun 2016 until Jul 2016]
Yuexin Ma [University of Hong Kong, PhD Student, from Jun 2016 until Jul 2016]
Théo Poisson [Inria, Intern, from Feb 2016 until May 2016]
Denis Salem [Inria, Intern, from Sep 2016]
Olzhas Turar [Kazakh National University, PhD student, from Sep 2016 until Nov 2016]

2. Overall Objectives

2.1. Overall Objectives

ALICE is a project-team in Computer Graphics. The fundamental aspects of this domain concern the interaction of *light* with the *geometry* of the objects. The lighting problem consists in designing accurate and efficient *numerical simulation* methods for the light transport equation. The geometrical problem consists in developing new solutions to *transform and optimize geometric representations*. Our original approach to both issues is to restate the problems in terms of *numerical optimization*. We try to develop solutions that are *provably correct*, *numerically stable* and *scalable*.

To reach these goals, our approach consists in transforming the physical or geometric problem into a numerical optimization problem, studying the properties of the objective function and designing efficient minimization algorithms. Besides Computer Graphics, our goal is to develop cooperations with researchers and people from the industry, who test applications of our general solutions to various domains, comprising CAD, industrial design, oil exploration, plasma physics... Our solutions are distributed in both open-source software (Graphite, OpenNL, CGAL) and industrial software (Gocad, DVIZ).

Since 2010, we started to develop techniques to model not only virtual objects, but also real ones. Our "modeling and rendering" research axis evolved, and we generalized our results on by-example texture synthesis to the production of real objects, using 3D printers. As compared to virtual objects, this setting defines higher requirements for the geometry processing techniques that we develop, that need to be adapted to both numerical simulation and computer-aided fabrication. We study how to include *computational physics* into the loop, and simulation methods for various phenomena (*e.g.*, fluid dynamics).

3. Research Program

3.1. Introduction

Computer Graphics is a quickly evolving domain of research. These last few years, both acquisition techniques (*e.g.*, range laser scanners) and computer graphics hardware (the so-called GPU's, for Graphics Processing Units) have made considerable advances. However, despite these advances, fundamental problems still remain open. For instance, a scanned mesh composed of hundred millions triangles cannot be used directly in real-time visualization or complex numerical simulation. To design efficient solutions for these difficult problems, ALICE studies two fundamental issues in Computer Graphics:

- the representation of the objects, *i.e.*, their geometry and physical properties;
- the interaction between these objects and light.

Historically, these two issues have been studied by independent research communities. However, we think that they share a common theoretical basis. For instance, multi-resolution and wavelets were mathematical tools used by both communities [29]. We develop a new approach, which consists in studying the geometry and lighting from the *numerical analysis* point of view. In our approach, geometry processing and light simulation are systematically restated as a (possibly non-linear and/or constrained) functional optimization problem. This type of formulation leads to algorithms that are more efficient. Our long-term research goal is to find a formulation that permits a unified treatment of geometry and illumination over this geometry.

3.2. Geometry Processing for Engineering

Keywords: Mesh processing, parameterization, splines

Geometry processing recently emerged (in the middle of the 90's) as a promising strategy to solve the geometric modeling problems encountered when manipulating meshes composed of hundred millions of elements. Since a mesh may be considered to be a *sampling* of a surface - in other words a *signal* - the *digital signal processing* formalism was a natural theoretic background for this subdomain (see *e.g.*, [30]). Researchers of this domain then studied different aspects of this formalism applied to geometric modeling.

Although many advances have been made in the geometry processing area, important problems still remain open. Even if shape acquisition and filtering is much easier than 30 years ago, a scanned mesh composed of hundred million triangles cannot be used directly in real-time visualization or complex numerical simulation. For this reason, automatic methods to convert those large meshes into higher level representations are necessary. However, these automatic methods do not exist yet. For instance, the pioneer Henri Gouraud often mentions in his talks that the *data acquisition* problem is still open [19]. Malcolm Sabin, another pioneer of the "Computer Aided Geometric Design" and "Subdivision" approaches, mentioned during several conferences of the domain that constructing the optimum control-mesh of a subdivision surface so as to approximate a given surface is still an open problem [28]. More generally, converting a mesh model into a higher level representation, consisting of a set of equations, is a difficult problem for which no satisfying solutions have been proposed. This is one of the long-term goals of international initiatives, such as the AIMShape European network of excellence.

Motivated by gridding application for finite elements modeling for oil and gas exploration, in the frame of the Gocad project, we started studying geometry processing in the late 90's and contributed to this area at the early stages of its development. We developed the LSCM method (Least Squares Conformal Maps) in cooperation with Alias Wavefront [24]. This method has become the de-facto standard in automatic unwrapping, and was adopted by several 3D modeling packages (including Maya and Blender). We explored various applications of the method, including normal mapping, mesh completion and light simulation [21].

However, classical mesh parameterization requires to partition the considered object into a set of topological disks. For this reason, we designed a new method (Periodic Global Parameterization) that generates a continuous set of coordinates over the object [26]. We also showed the applicability of this method, by proposing the first algorithm that converts a scanned mesh into a Spline surface automatically [23].

We are still not fully satisfied with these results, since the method remains quite complicated. We think that a deeper understanding of the underlying theory is likely to lead to both efficient and simple methods. For this reason, in 2012 we studied several ways of discretizing partial differential equations on meshes, including Finite Element Modeling and Discrete Exterior Calculus. In 2013, we also explored Spectral Geometry Processing and Sampling Theory (more on this below).

3.3. Computer Graphics

Keywords: texture synthesis, shape synthesis, texture mapping, visibility

Content creation is one of the major challenges in Computer Graphics. Modeling shapes and surface appearances which are visually appealing and at the same time enforce precise design constraints is a task only accessible to highly skilled and trained designers.

In this context the team focuses on methods for by-example content creation. Given an input example and a set of constraints, we design algorithms that can automatically generate a new shape (geometry+texture). We formulate the problem of content synthesis as the joint optimization of several objectives: Preserving the local appearance of the example, enforcing global objectives (size, symmetries, mechanical properties), reaching user defined constraints (locally specified geometry, contacts). This results in a wide range of optimization problems, from statistical approaches (Markov Random fields), to combinatorial and linear optimization techniques.

As a complement to the design of techniques for automatic content creation, we also work on the representation of the content, so as to allow for its efficient manipulation. In this context we develop data structures and algorithms targeted at massively parallel architectures, such as GPUs. These are critical to reach the interactive rates expected from a content creation technique. We also propose novel ways to store and access content defined along surfaces [27] or inside volumes [18] [22].

The team also continues research in core topics of computer graphics at the heart of realistic rendering and realistic light simulation techniques; for example, mapping textures on surfaces, or devising visibility relationships between 3D objects populating space.

4. Application Domains

4.1. Geometric Tools for Simulating Physics with a Computer

Numerical simulation is the main targeted application domain for the geometry processing tools that we develop. Our mesh generation tools are tested and evaluated in the frame of our cooperation with the Gocad consortium, with applications in oil exploration and geomechanics, through co-advised Ph.D. thesis (Arnaud Botella, Julien Renaudeau). We think that the hex-dominant meshes that we generate have geometrical properties that make them suitable for some finite element analyses. We work on evaluating and measuring their impact with simple problems (heat equation, linear elasticity) and then practical applications (unfolding geological layer), with the Ph.D. thesis of Maxence Reberol.

In numerical simulation, developing discrete formulations that satisfy the conservation laws (conservation of mass, conservation of energy, conservation of momentum) is important to ensure that the numerical simulation faithfully reflects the behavior of the physics. There are interesting relations with optimal transport theory, as explained by Benamou and Brenier who developed a numerical algorithm for optimal transport that uses a fluid dynamics formulation [17]. Conversely, some dynamics can be approximated by a series of optimal transport problems, as in the Jordan-Kinderlehrer-Otto scheme [20] and in recent works by Mérigot. We started developing efficient geometric algorithms and optimisation methods that may serve as the basis for implementing these numerical methods in 3D. We started discussions / cooperation projects with Quentin Mérigot (MOKAPLAN project).

4.2. Fabrication

Our work around fabrication and additive manufacturing finds applications in different fields. Our algorithms for fast geometric computations on solids (boolean operations, morphological operations) are useful to model a variety of shapes, from mechanical engineering parts to prosthetics for medical applications.

Our by-example techniques allow for simpler modeling and processing of very intricate geometries and therefore also find applications in art and design, for unusual shapes that would be very difficult to obtain otherwise. Extensions of these techniques also find applications for reproducing naturally occurring micro-structures from a scanned sampled.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Geometry processing

Meshes composed of hexahedra (deformed cubes) are desirable for certain numerical simulations, they can improve both performances and precision. They are very difficult to generate. We developed in 2010 one of the first fully automatic algorithms that generates a "hex-dominant" hybrid mesh (top part of the image), with hexahedra and other elements (colored). This year, we made a quantum leap, and significantly reduced the number of non-hex elements (bottom part of the image). Our approach is based on an optimization of a direction field [11] and a global parameterization steered by the direction field [9].

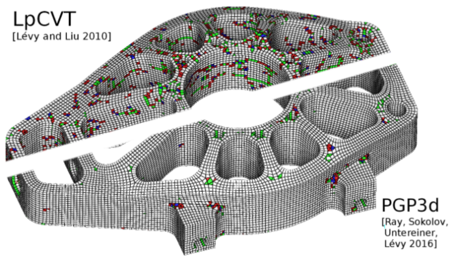

Figure 1. Improvements in hexahedral dominant remeshing.

5.1.2. Additive manufacturing

The advent of additive manufacturing enables the fabrication of shapes with unprecedented complexity, in particular embedding intricate micro-structures with details in the order of tens of microns. There is a strong interest in different fields for such structures, in medical science (prosthetics), mechanical engineering (strong but lightweight materials), art and design (aesthetics, material strength and flexibility). Unfortunately, we lack the software tools to model these structures efficiently. This year we made two significant advances in this area. We first proposed a novel methodology to create procedural micro-structures that exhibit good mechanical properties and can be fabricated [7]. As the definition of the micro-structure is procedural, they are not precomputed. Instead their geometry is evaluated on the fly, slice after slice, during the additive manufacturing process. Yet, their elasticity can be progressively varied within the shape to align with geometric features. Our second contribution is a novel algorithm to synthesize intricate filigree patterns along a surface, from basic elements [5]. This is achieved by relaxing a strict geometric packing problem by to allow for partial overlaps between elements that preserve local geometric details. The shapes are optimized for strength during the synthesis.

6. New Software and Platforms

6.1. GEOGRAM

GEOGRAM : A functions library for geometric programming
KEYWORD: 3D modeling

GEOGRAM is a programming library with a set of basic geometric algorithms, such as search data structures (AABB tree, Kd tree), geometric predicates, triangulations (Delaunay triangulation, Regular triangulation), intersection between a simplicial mesh and a Voronoi diagram (restricted Voronoi diagram). GEOGRAM also includes a code generator for predicates (PCK: Predicate Construction Kit) and an efficient implementation of expansion arithmetics in arbitrary precision. GEOGRAM is shipped with WARPDRIVE, the first program that computes semi-discrete optimal transport in 3D.

- Participant: Bruno Lévy
- Contact: Bruno Lévy
- URL: http://alice.loria.fr/software/geogram/doc/html/index.html

6.2. GLE

GraphiteLifeExplorer
KEYWORDS: 3D modeling - Biology
GLE is a 3D modeler, developed as a plugin of Graphite, dedicated to molecular biology. Biologists need simple spatial modeling tools to help in understanding the role of the relative position of objects in the functioning of the cell. In this context, we develop a tool for easy DNA modeling. The tool generates DNA along any user-given curve, open or closed, allows for fine-tuning of atoms position and, most importantly, exports to PDB (the Protein Daba Bank file format).

- Participant: Samuel Hornus
- Partner: Fourmentin Guilbert foundation
- Contact: Samuel Hornus
- URL: https://members.loria.fr/samuel.hornus/FFG/gle.html

6.3. Graphite

Graphite: The Numerical Geometry Workbench
KEYWORDS: 3D modeling - Numerical Geometry - Texturing - Lighting - CAD - Visualization
Graphite is an experimental 3D modeler, built on top of the Geogram programming library. It has data structures and efficient OpenGL visualization for pointsets, surfacic meshes (triangles and polygons), volumetric meshes (tetrahedra and hybrid meshes). It has state-of-the-art mesh repair, remeshing, reconstruction algorithms. It also has an interface to the Tetgen tetrahedral mesh generator (by Hang Si). This year, Graphite3 was released. It is a major rewrite, based on Geogram, with increased software quality standards (zero warnings on all platforms, systematic documentation of all classes / all functions / all parameters, dramatically improved performances). It embeds Geogram (and optionally Vorpaline) with an easy-to-use Graphic User Interface.
Graphite is a dedicated software platform in numerical geometry that enables, among other things, 3D modelling and texture baking.

- Participants: Dobrina Boltcheva, Samuel Hornus, Bruno Lévy, David Lopez, Jeanne Pellerin and Nicolas Ray
- Contact: Bruno Lévy
- URL: http://alice.loria.fr/software/graphite

6.4. IceSL

The software allows us to modelize throught CSG's operations 3D's objects. These objects can be directly prepared to be send through a 3d printer without forming an intermediary mesh.

- Participants: Sylvain Lefebvre, Jérémie Dumas, Jean Hergel, Frederic Claux, Jonas Martinez Bayona and Samuel Hornus
- Contact: Sylvain Lefebvre
- URL: http://shapeforge.loria.fr/icesl

6.5. LibSL

LibSL: Simple Library For Graphics
LibSL is a toolbox for rapid prototyping of computer graphics algorithms, under both OpenGL, DirectX 9/10, Windows and Linux.

- Participant: Sylvain Lefebvre
- Contact: Sylvain Lefebvre
- URL: http://members.loria.fr/Sylvain.Lefebvre/libsl

6.6. OpenNL

OpenNL: Open Numerical Library
KEYWORDS: 3D modeling - Numerical algorithm
SCIENTIFIC DESCRIPTION

Open Numerical Library is a library for solving sparse linear systems, especially designed for the Computer Graphics community. The goal of OpenNL is to be as small as possible, while offering the subset of functionalities required by this application field. The Makefiles of OpenNL can generate a single .c + .h file, very easy to integrate in other projects. The distribution includes an implementation of the Least Squares Conformal Maps parameterization method.

- Participants: Bruno Lévy, Rhaleb Zayer and Nicolas Ray
- Contact: Bruno Lévy
- URL: http://alice.loria.fr/index.php/software/4-library/23-opennl.html

6.7. VORPALINE

VORPALINE mesh generator
KEYWORDS: 3D modeling - Unstructured heterogeneous meshes
VORPALINE is a surfacic and volumetric mesh generator, for simplicial meshes (triangles and tetrahedra), for quad-dominant and hex-dominant meshes.

- Participant: Bruno Lévy
- Contact: Bruno Lévy
- URL: http://alice.loria.fr/index.php/erc-vorpaline.html

7. New Results

7.1. Hexahedral-dominant Remeshing

Participants: Dmitry Sokolov, Nicolas Ray, Bruno Lévy, Maxence Reberol

Representing the geometry of complex objects in a computer is usually achieved by a mesh: the object is decomposed in cells that have a simple geometry. Each cell is defined by a set of facets. The simplest choice is to use meshes with tetrahedral cells that are relatively easy to produce and to work with. However, some applications involving numerical simulations better work with hexahedral cells. Such hexahedral meshes are very difficult to produce, even when it is completely done by a designer. Our objective is to relax the intrinsic difficulties of full hexahedral remeshing by allowing the process to generate a few tetrahedra in the hexahedral mesh (hexahedral-dominant meshes). Our approach is to produce as many hexahedra as possible by filling most of the volume with a deformed 3D grid, and to rely on more classic meshing techniques everywhere else. We also develop tools to evaluate how our remeshing impacts results of FEM simulations.

7.1.1. Generation of Hexahedral-dominant Meshes

The traditional approach to produce hexahedral dominant meshes is by advancing front: first hexahedra are produced near the object boundary, then additionals hexahedra are attached to them. An alternative solution is to consider an hexahedral mesh as a deformed 3D grid: the hexahedral remeshing problem is then restated as finding the (geometric) deformation that will transform the hexahedral mesh into the regular grid. This approach is able to generate very good hexhaderal meshes, but it is often impossible to entirely remesh the input object.

Our objective is to produce hexahedra from the mapping approach, then complete the mesh with traditional approaches that may leave some tetrahedra. We proposed a first solution [9]: we compute a mapping, extract the vertices of the deformed 3D grid, generate a tetrahedral mesh having these vertices, then merge sets of tetrahedra into hexahedra with an extension of [25]. Using the mapping as a heuristic made this solution very competitive with other hexahedral dominant methods. We are now developing a software pipeline that makes it easy for different algorithms (frame field, mapping and classic remeshing) to work together. With a simple implementation of each step, we already observe better performances than previous works, and we foresee many opportunities to improve it.

7.1.2. Impact on FEM Performance

It is admitted by our scientific community that hexahedral meshes are better than tetrahedral meshes for some FEM simulation. We would like to demonstrate evidence of this belief, including fair comparisons with equal running time and/or result accuracy, with the best function basis for each case. For hexahedral dominant meshes, we have developed a new specific function basis devoted to properly link tetrahedral and hexahedral elements. Using a combination of tri-linear and quadratic hexahedra, we can build an approximation space made of continuous functions, even at non-conforming interfaces between hexahedra and tetrahedra. But in practice, hexahedral-dominant meshes are mainly useful to mesh complicated 3D domains. In such cases, there are no analytical solutions of partial differential equations and thus it is not straightforward to evaluate the accuracy of a new numerical method. To measure the differences between finite element solutions defined on different meshes of the same 3D model, we are developing a fast and efficient sampling method which exploits GPU hardware. These topics are addressed in the (ongoing) Ph.D. thesis of Maxence Reberol.

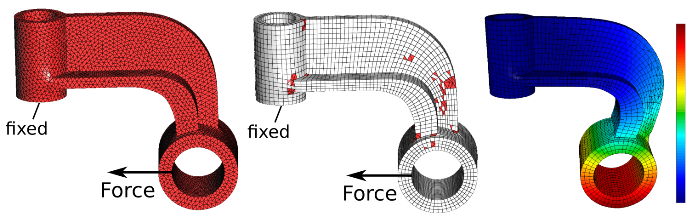

Figure 2. Mechanical problem on the Hanger 3D model. (left) Sandard tetrahedral mesh. (center) Our hex-dominant mesh, hex in gray and tet in red. (right) Solution of the problem with mixed hexahedral-tetrahedral finite elements, color is the amplitude of the displacement.

7.2. Optimal transport

Participant: Bruno Lévy

7.2.1. Optimal transport:

Optimal Transport is not only a fundamental problem with a rich structure, but also a new computational tool, with many possible applications. To name but a few, applications of Optimal Transport comprise image registration, reflector and refractor design, histogram interpolation, artificial intelligence. In astrophysics, it is used by Early Universe Reconstruction, a difficult inverse problem that reconstructs the time evolution of the universe from the observed current state. It can be also used in meteorology, to simulate certain phenomena (semi-geostrophic currents). It is also the main component of solvers for certain equations, based on a variational formulation that leads to a gradient flow. All these applications and future developments depend on a single component: an efficient solver for the Monge-Ampère equation. We developed a new algorithm that overcome by several order of magnitude the speed of the classical "auction algorithm" (that solves in $O(n \log(n))$ a discrete version of the problem). The *semi-discrete* version of the problem that we study can be solved by extremizing a smooth objective function, thus a significantly faster speed is obtained as compared to the previous combinatorial algorithm. This year we improved our Quasi-Newton solver and replaced it with a Full-Newton solver, that gains one additional order of magnitude in speed, and we can solve semi-discrete problems with 1 million Dirac masses in a matter of minutes. We also experimented with applications of this solver to fluid simulation. Last winter (December 2015) Wenping Wang visited Nancy, and we discussed several ideas on Optimal Transport. We proposed together this year (2016) a new method to sample a surface with a power diagram [31]. The positions of the samples are optimized by a criterion similar to centroidal Voronoi tessellations, and the associated weights are used to control the areas of the power cells with prescribed values. We give the expressions of the derivatives of the combined objective function, and propose a quasi-Newton algorithm to optimize it. We describe several applications of the algorithm.

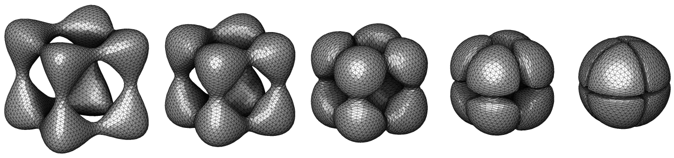

Figure 3. Semi-discrete optimal transport between a shape and a sphere, computed by our algorithm

7.3. Spectral Clustering of Plant Units From 3D Point Clouds

Participant: Dobrina Boltcheva

High-resolution terrestrial Light Detection And Ranging (tLiDAR), a 3-D remote sensing technique, has recently been applied for measuring the 3-D characteristics of vegetation from grass to forest plant species. The resulting data are known as a point cloud which shows the 3-D position of all the hits by the laser beam giving a raw sketch of the spatial distribution of plant elements in 3-D, but without explicit information on their geometry and connectivity. We have developed a new approach based on a delineation algorithm that clusters a point cloud into elementary plant units such as internodes, petioles and leaves. The algorithm creates a graph (points + edges) to recover plausible neighboring relationships between the points and embeds this graph in a spectral space in order to segment the point-cloud into meaningful elementary plant units. This work has been published in the International Journal of Remote Sensing [6].

7.4. Surface Reconstruction From 3D Point Clouds

Participants: Dobrina Boltcheva, Bruno Lévy

We have developed a practical reconstruction algorithm that generates a surface triangulation from an input pointset. In the result, the input points appear as vertices of the generated triangulation. The algorithm has several desirable properties: it is very simple to implement, it is time and memory efficient, and it is trivially parallelized. On a standard hardware (core i7, 16Gb) it takes less than 10 seconds to reconstruct a surface from 1 million points, and scales-up to 36 million points (then it takes 350 seconds). On a smartphone (ARMV7 Neon, quad core), it takes 55 seconds to reconstruct a surface from 900K points. The algorithm computes the Delaunay triangulation of the input pointset restricted to a "thickening" of the pointset (similarly to several existing methods, like alpha-shapes, crust and co-cone). By considering the problem from the Voronoi point of view (rather than Delaunay), we use a simple observation (radius of security) that makes the problem simpler. The Delaunay triangulation data structure and associated algorithms are replaced by simpler ones (KD-Tree and convex clipping) while the same set of triangles is provably obtained. The restricted Delaunay triangulation can thus be computed by an algorithm that is not longer than 200 lines of code, memory efficient and parallel. The so-computed restricted Delaunay triangulation is finally post-processed to remove the non-manifold triangles that appear in regions where the sampling was not regular/dense enough. Sensitivity to outliers and noise is not addressed here. Noisy inputs need to be pre-processed with a pointset filtering method. In the presented experimental results, we are using two iterations of projection onto the best approximating plane of the 30 nearest neighbors (more sophisticated ones may be used if the input pointset has many outliers).

This work has been published in the Research Report [13] and is currently in revision for Eurographics 2017.

7.5. Microstructures for additive manufacturing

Participants: Jonas Martinez, Sylvain Lefebvre

Nowadays, there is a big interest in the functional optimization of microstructures for additive manufacturing, as reflected by the high number of recent publications on the subject. This also comes not only from research but also industry, as controlling the macroscopic elasticity of materials has a wide range of industrial applications. For instance, to fabricate flexible prosthetic body parts, or to produce rigid but porous prosthetics for surgery. In particular, controlling material elasticity will enable the design of lightweight and resistant materials, and in turn, reduce material consumption.

Most of the existing software either optimize for periodic tilings of microstructures, or generate random microstructures without precise control of their functionality. We recently introduced a method [7] to generate stochastic structures (figure 4) while having unique computational advantages, and precisely controlling their functionality. Our optimization approach of stochastic porous structures deviates significantly from both the periodic tiling of microstructures and the optimization of macrostructures, by making a link between microstructures, and procedural solid textures with controlled statistics in Computer Graphics. We believe there are many other such structures left to be discovered, and hope our work will spark further interest in procedurally generated, stochastic microstructures.

7.6. Towards Zero-Waste Furniture Design

Participants: Bongjin Koo, Jean Hergel, Sylvain Lefebvre, Niloy J. Mitra.

This project considered the optimization of parametric models of furniture to reduce the wastage of material used to fabricate the model. Our approach uses a 2D packing algorithm to pack the different parts of the furniture in a wooden plank. Then we optimize locally the wastage by editing smoothly the parameters with only moving smoothly the parts in the packing space. We produced full size objects with laser cutter to prove the efficiency of our method. This work has been accepted in Transaction on Visualization and Computer Graphics.

7.7. Anti-aliasing for fused filament deposition

Participants: Hai-Chuan Song, Nicolas Ray, Dmitry Sokolov, Sylvain Lefebvre

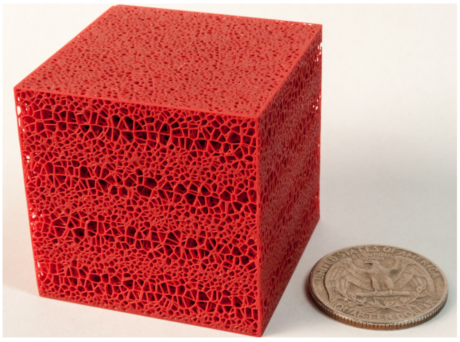

Figure 4. Anisotric microstructures

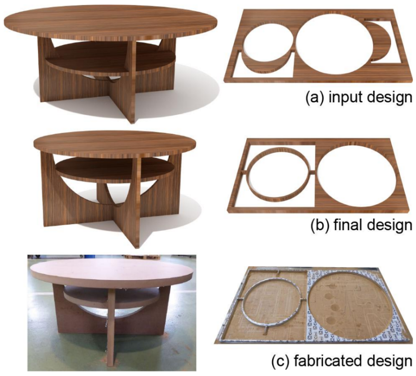

Figure 5. Our technique modifies the parameters of the input design (a) to improve the packing and waste less material (b). The produced furniture is shown in (c).

Layered manufacturing inherently suffers from staircase defects along surfaces that are gently sloped with respect to the build direction. Reducing the slice thickness improves the situation but never resolves it completely as flat layers remain a poor approximation of the true surface in these regions. In addition, reducing the slice thickness largely increases the print time. In this project we focus on a simple yet effective technique to improve the print accuracy for layered manufacturing by filament deposition. Our method [16] works with standard three-axis 3D filament printers (e.g. the typical, widely available 3D printers), using standard extrusion nozzles. It better reproduces the geometry of sloped surfaces without increasing the print time. Our key idea is to perform a local anti-aliasing, working at a sub-layer accuracy to produce slightly curved deposition paths and reduce approximation errors. We show that the necessary deviation in height compared to standard slicing is bounded by half the layer thickness. Therefore, the height changes remain small and plastic deposition remains reliable. We further split and order paths to minimize defects due to the extruder nozzle shape, avoiding any change in the existing hardware. We apply and analyze our approach on 3D printed examples, showing that our technique greatly improves surface accuracy and silhouette quality while keeping the print time nearly identical.

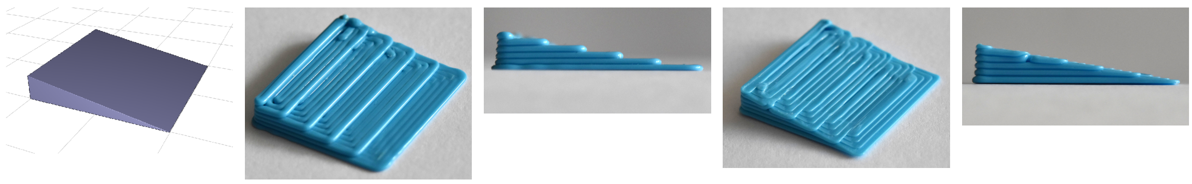

Figure 6. Printing a wedge model clearly reveals the staircase defects that plague 3D printing. (a) Input 3D model; the bottom edge length is 20mm and the angle of the incline plane is 10. (b) Global view and (c) side view of a standard, flat layer printed result. (d) Global view and (e) side view of our anti-aliased printed result, revealing the improvement in surface accuracy and silhouette smoothness

8. Partnerships and Cooperations

8.1. Regional Initiatives

CPER (2014-2020) 50 k€. Sylvain Lefebvre coordinates a work package for the CPER 2014-2020. It involves several members of ALICE as well as laboratories within the Nancy area (Institut Jean Lamour, LRGP, ERPI). Our goal is to consider the interaction between software and material in the additive manufacturing process, with a focus on filament-based printers.

PIC (2015-2017) 150 k€. The PIC project (Polymères Innovants Composites) is a collaboration between Inria, Institut Jean Lamour and Ateliers Cini, funded by Région Lorraine. The goal is to develop a new additive manufaturing process using filament of composite materials with applications in mechanical engineering and the medical domain. Our goal in the project is to provide novel ways to deposit the filament that is better suited to the considered materials and improves the quality of the final parts.

8.2. National Initiatives

8.2.1. ANR BECASIM (2013 – 2016)

890 k€. X. Antoine heads the second partner, which includes Bruno Lévy. Budget for Nancy: 170 k€ of which 100 k€ are for IECL (team CORIDA). This project is managed by Inria. Becasim is a thematic "Numerical Models" ANR project granted by the French Agence Nationale de la Recherche for years 2013-2016. The

acronym Becasim is related to Bose-Einstein Condensates: Advanced SIMulation Deterministic and Stochastic Computational Models, HPC Implementation, Simulation of Experiments. The members of the ANR Project Becasim belong to 10 different laboratories.

8.3. European Initiatives

8.3.1. FP7 & H2020 Projects

8.3.1.1. SHAPEFORGE

Title: ShapeForge: By-Example Synthesis for Fabrication
Programm: FP7
Duration: December 2012 - November 2017
Coordinator: Inria
Inria contact: Sylvain Lefebvre

Despite the advances in fabrication technologies such as 3D printing, we still lack the software allowing for anyone to easily manipulate and create useful objects. Not many people possess the required skills and time to create elegant designs that conform to precise technical specifications. 'By–example' shape synthesis methods are promising to address this problem: New shapes are automatically synthesized by assembling parts cutout of examples. The underlying assumption is that if parts are stitched along similar areas, the result will be similar in terms of its low–level representation: Any small spatial neighborhood in the output matches a neighborhood in the input. However, these approaches offer little control over the global organization of the synthesized shapes, which is randomized. The ShapeForge challenge is to automatically produce new objects visually similar to a set of examples, while ensuring that the generated objects can enforce a specific purpose, such as supporting weight distributed in space, affording for seating space or allowing for light to go through. These properties are crucial for someone designing furniture, lamps, containers, stairs and many of the common objects surrounding us. The originality of our approach is to cast a new view on the problem of 'by–example' shape synthesis, formulating it as the joint optimization of 'by–example' objectives, semantic descriptions of the content, as well as structural and fabrication objectives. Throughout the project, we will consider the full creation pipeline, from modeling to the actual fabrication of objects on a 3D printer. We will test our results on printed parts, verifying that they can be fabricated and exhibit the requested structural properties in terms of stability and resistance.

8.4. International Initiatives

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

8.4.1.1. PREPRINT3D

Title: Model Preparation for 3D Printing
International Partner (Institution - Laboratory - Researcher):
University of Hong Kong, Computer science department, with Li-Yi Wei and Wenping Wang
Start year: 2014

We seek to develop novel ways to prepare objects for 3D printing which better take into account limitations of the fabrication processes as well as real-world properties such as the mechanical strength of the printed object. This is especially important when targeting an audience which is not familiar with the intricacies of industrial design. We target complex, intricate shapes such as models of vegetation and highly detailed meshes, as well as models with thin walls such as architectural models. Our methods will modify the object geometry and topology while remaining as close as possible to its initial appearance.

8.4.2. Inria International Partners

8.4.2.1. Informal International Partners

We have on-going collaborations with Marc Alexa (TU Berlin) regarding slicing algorithms for additive manufacturing and Niloy Mitra (University College London) on minimal wastage design of furniture.

8.5. International Research Visitors

8.5.1. Visits of International Scientists

8.5.1.1. Internships

Denis Salem (CESI-EXIA), 6-months intern started in September 2016, working on point distributions along surfaces using GPU algorithms. Théo Poisson (CESI-EXIA) was an intern from February to May 2016, working on quality testing and improvements to our software IceSL. Yuexin Ma, PhD student with Wenping Wang (HKU), 1 month visit in the context of the PrePrint3D associated team.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. General Chair, Scientific Chair

Sylvain Lefebvre is program co-chair for SMI 2017.

9.1.1.2. Member of the Organizing Committees

Bruno Lévy was conference co-chair of GMP 2016.

9.1.2. Scientific Events Selection

9.1.2.1. Chair of Conference Program Committees

Bruno Lévy was member of the program committee of ACM/EG Symposium on Geometry Processing, Pacific Graphic, Shape Modeling International

9.1.2.2. Member of the Conference Program Committees

Sylvain Lefebvre was member of the SIGGRAPH 2016 program committee, and is a member of the EUROGRAPHICS 2017 program committee.

9.1.2.3. Reviewer

- Jonas Martinez: Eurographics'16 Short papers.
- N. Ray: SIGGRAPH, SIGGRAPH ASIA, eurographics

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

Sylvain Lefebvre is associate editor for ACM TOG. Bruno Lévy is associate editor of ACM Transactions on Graphics, The Visual Computer and Graphical Models

9.1.3.2. Reviewer - Reviewing Activities

- D. Sokolov: Computer Graphics Forum, The Visual Computer
- N. Ray: ACM TOG, TVCG, Electronics Letters
- Dobrina Boltcheva : International Journal of Discrete & Computational Geometry
- Jonas Martinez: Computers & Graphics journal.
- Laurent Alonso: Graphs and Combinatorics, Discrete Applied Mathematics, ACM Translation of Algorithms, ESA 2016, LATIN 2016

9.1.4. Invited Talks

- Dmitry Sokolov: "Towards hexahedral meshes" Numerical geometry, grid generation and scientific computing NUMGRID 2016, Moscow
- Sylvain Lefebvre: Computer Graphics lab of Aachen, led by Pr. Leif Kobbelt
- Sylvain Lefebvre: IST Austria, visiting Pr. Bernt Bickel
- Sylvain Lefebvre: invited at CNR Imati (Genova, Italy) for a week to present his work and collaborate on a joint survey paper submitted to EUROGRAPHICS 2017.

9.1.5. Scientific Expertise

Bruno Lévy evaluated projects for the ANR, for the European Research Council.

9.1.6. Research Administration

Samuel Hornus was moderator of the CDT (Commission for Technological Development) of Inria nancy.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Licence : Enseignant, titre du cours, nombre d'heures en équivalent TD, niveau (L1, L2, L3), université, pays

Licence : Cédric Zanni, Informatique 1, 20h ETD, L3, École des Mines de Nancy, France

License: Dobrina Boltcheva, Licence Pro ISN, Computer Graphics 20h, Image Processing 20h, IUT Saint-Dié-des-Vosges

License: Dobrina Boltcheva, 2A DUT INFO, Advanced Java Programming 100h, IUT Saint-Dié-des-Vosges

License: Dobrina Boltcheva, 1A DUT INFO, Programming 60h, IUT Saint-Dié-des-Vosges

Licence : Dmitry Sokolov, Informatique graphique, 55h ETD, L1, Université de Lorraine, France

Licence : Dmitry Sokolov, Programmation Avancée, 40h ETD, L2, Université de Lorraine, France

Licence : Dmitry Sokolov, Logique, 20h ETD, L3, Université de Lorraine, France

Licence : Dmitry Sokolov, Introduction à la robotique mobile, 30h ETD, L2, Université de Lorraine, France

License : Samuel Hornus, Mathématiques Appliquées pour l'Informatique, 32 h ETD, L3, Télécom Nancy

Master : N. Ray, communication, 10h equivalent TD, M1, Universitée de Lorraine, France

Master :Cédric Zanni, Software Engineering, 19h ETD, M1, École des Mines de Nancy, France

Master :Cédric Zanni, Operating System, 14h ETD, M1, École des Mines de Nancy, France

Master :Cédric Zanni, Modèles et simulations d'instrument de musique, 9h ETD, M1, École des Mines de Nancy, France

Master :Dmitry Sokolov, Optimisation Combinatoire, 30h ETD, M1, Université de Lorraine, France

Master :Dmitry Sokolov, Infographie, 30h ETD, M1, Université de Lorraine, France

Master :Dmitry Sokolov, Algorithmique et programmation, 45h ETD, M1, Université de Lorraine, France

Master :Dmitry Sokolov, Algorithmique et Programmation Avancée, 60h ETD, M2, Université de Lorraine,France

Master, Sylvain Lefebvre, Programmation pour le jeux vidéo, 30h ETD, Ecole des Mines de Nancy, France.

Master, Sylvain Lefebvre, Introduction au parallélisme et au graphisme, 9h ETD, ENSG Nancy, France.

Master, Sylvain Lefebvre, Introduction à la fabrication additive, 9h ETD, ENSEM Nancy, France.

Master, Sylvain Lefebvre, Synthèse procédurale pour le design, 9h ETD, ENSAD, Nancy, France.

E-learning

Pedagogical resources tinyRender: Dmitry Sokolov, Computer graphics course. Short series of lectures on what is under the hood of OpenGL/DirectX. The course is already adopted in several universities throughout the world, and is now included in the distribution of Bullet physics library. Microsoft includes its C# port in the distribution of Xamarin Workbooks .

9.2.2. Supervision

HdR : Dmitry Sokolov, *Modélisation géométrique*, Université de Lorraine, 10 juin 2016

PhD thesis submitted, defense 01/02/2017 : Jean Hergel, *Modeling under Fabrication Constraints*, Oct. 2013, supervised by Sylvain Lefebvre

PhD thesis submitted, defense 03/02/2017 : Jérémie Dumas, *By-example shape synthesis for Fabrication*, Sept. 2013, supervised by Sylvain Lefebvre

PhD in progress : Maxence Reberol, *Finite elements for non-conformal mixed hexahedral-tetrahedral meshes*, Janvier 2015, co-supervised by Bruno Lévy and Sylvain Lefebvre

9.2.3. Juries

Dobrina Boltcheva was a member of the recruitment committee for an associate professor position (maître de conférence) at the University of Poitiers (MCF 27 - XLIM/IRIAF).

Sylvain Lefebvre was a member of the CR2 recruitment jury for Inria Nancy Grand-Est. He was reviewer ('rapporteur') for the PhD defense of Hugo Loi (Université de Grenoble).

9.3. Popularization

Sylvain Lefebvre participated in the 2016 science festival (stand and general public conference), and gave a presentation in front of an industrial public in an event organized by Fondation Charles Hermite.

10. Bibliography

Major publications by the team in recent years

[1] J. DUMAS, J. HERGEL, S. LEFEBVRE.*Bridging the Gap: Automated Steady Scaffoldings for 3D Printing*, in "ACM Trans. Graph.", July 2014, vol. 33, n^{o} 4, p. 98:1–98:10, http://doi.acm.org/10.1145/2601097.2601153.

[2] J. MARTÍNEZ, J. DUMAS, S. LEFEBVRE, L.-Y. WEI.*Structure and Appearance Optimization for Controllable Shape Design*, in "ACM Trans. Graph.", October 2015, vol. 34, n^{o} 6, p. 229:1–229:11, http://doi.acm.org/10.1145/2816795.2818101.

[3] J. MARTÍNEZ, J. DUMAS, S. LEFEBVRE.*Procedural Voronoi Foams for Additive Manufacturing*, in "ACM Transactions on Graphics", 2016, vol. 35, p. 1 - 12 [*DOI :* 10.1145/2897824.2925922], https://hal.archives-ouvertes.fr/hal-01393741.

[4] D. SOKOLOV, N. RAY, L. UNTEREINER, B. LÉVY.*Hexahedral-Dominant Meshing*, in "ACM Transactions on Graphics", 2016, vol. 35, n^{o} 5, p. 1 - 23 [*DOI :* 10.1145/2930662], https://hal.inria.fr/hal-01397846.

Publications of the year

Articles in International Peer-Reviewed Journal

[5] W. CHEN, X. XIA, S. XIN, Y. XIA, S. LEFEBVRE, W. WANG.*Synthesis of Filigrees for Digital Fabrication*, in "ACM Transactions on Graphics", July 2016, vol. 35, n^{o} 4 [*DOI :* 10.1145/2897824.2925911], https://hal.inria.fr/hal-01401520.

[6] F. HÉTROY-WHEELER, E. CASELLA, D. BOLTCHEVA.*Segmentation of tree seedling point clouds into elementary units*, in "International Journal of Remote Sensing", 2016, vol. 37, n^{o} 13, p. 2881-2907 [*DOI :* 10.1080/01431161.2016.1190988], https://hal.inria.fr/hal-01285419.

[7] J. MARTÍNEZ, J. DUMAS, S. LEFEBVRE.*Procedural Voronoi Foams for Additive Manufacturing*, in "ACM Transactions on Graphics", 2016, vol. 35, p. 1 - 12 [*DOI :* 10.1145/2897824.2925922], https://hal.archives-ouvertes.fr/hal-01393741.

[8] J. PELLERIN, B. LÉVY, G. CAUMON, A. BOTELLA.*Automatic surface remeshing of 3D structural models at specified resolution: A method based on Voronoi diagrams*, in "Computers and Geosciences", March 2016, vol. 62, p. 103-116 [*DOI :* 10.1016/J.CAGEO.2013.09.008], https://hal.inria.fr/hal-00924622.

[9] D. SOKOLOV, N. RAY, L. UNTEREINER, B. LÉVY.*Hexahedral-Dominant Meshing*, in "ACM Transactions on Graphics", 2016, vol. 35, n^{o} 5, p. 1 - 23 [*DOI :* 10.1145/2930662], https://hal.inria.fr/hal-01397846.

International Conferences with Proceedings

[10] S. HORNUS, S. LEFEBVRE, J. DUMAS, F. CLAUX.*Tight printable enclosures and support structures for additive manufacturing*, in "Eurographics Workshop on Graphics for Digital Fabrication", Lisbonne, Portugal, A. M. E. SÁ, N. PIETRONI, K. R. ECHAVARRIA (editors), The Eurographics Association, May 2016, https://hal.inria.fr/hal-01399931.

[11] N. RAY, D. SOKOLOV, B. LÉVY.*Practical 3D frame field generation*, in "SIGGRAPH ASIA 2016", macao, Macau SAR China, December 2016, vol. 35, p. 1 - 9, https://hal.inria.fr/hal-01397711.

[12] T. REINER, S. LEFEBVRE.*Interactive Modeling of Support-free Shapes for Fabrication*, in "EUROGRAPHICS", Lisbonne, Portugal, Proceedings of EUROGRAPHICS (short papers), May 2016, https://hal.inria.fr/hal-01401470.

Research Reports

[13] D. BOLTCHEVA, B. LÉVY.*Simple and Scalable Surface Reconstruction*, LORIA - Université de Lorraine ; Inria Nancy, July 2016, https://hal.archives-ouvertes.fr/hal-01349023.

[14] M. REBEROL, B. LÉVY.*Low-order continuous finite element spaces on hybrid non-conforming hexahedral-tetrahedral meshes*, Inria Nancy, équipe ALICE, May 2016, https://hal.archives-ouvertes.fr/hal-01313285.

Other Publications

[15] N. RAY, D. SOKOLOV.*On Smooth Frame Field Design*, January 2016, working paper or preprint [*DOI :* 10.1145/1559755.1559763], https://hal.inria.fr/hal-01245657.

[16] H.-C. SONG, N. RAY, D. SOKOLOV, S. LEFEBVRE.*Anti-aliasing for fused filament deposition*, September 2016, arXiv, https://hal.inria.fr/hal-01400686.

References in notes

[17] J.-D. BENAMOU, Y. BRENIER.*A computational fluid mechanics solution to the Monge-Kantorovich mass transfer problem*, in "Numerische Mathematik", 2000, vol. 84, n^{o} 3, p. 375–393.

[18] I. GARCÍA, S. LEFEBVRE, S. HORNUS, A. LASRAM.*Coherent parallel hashing*, in "ACM Trans. Graph.", December 2011, vol. 30, 161:1, http://doi.acm.org/10.1145/2070781.2024195.

[19] H. Gouraud.*Continuous Shading of Curved Surfaces*, in "IEEE Trans. Comput.", June 1971, vol. 20, n° 6, p. 623–629, http://dx.doi.org/10.1109/T-C.1971.223313.

[20] R. Jordan, D. Kinderlehrer, F. Otto.*The Variational Formulation of the Fokker-Planck Equation*, in "SIAM J. Math. Anal", 1999, vol. 29, p. 1–17.

[21] G. Lecot, B. Lévy, L. Alonso, J.-C. Paul.*Master-Element Vector Irradiance for Large Tessellated Models*, in "Graphite conf. proc.", ACM, 2005, p. 315-322.

[22] S. Lefebvre, S. Hornus, A. Lasram.*Per-pixel lists for single pass A-buffer*, in "GPUPro 5", 2014.

[23] W. C. Li, N. Ray, B. Lévy.*Automatic and Interactive Mesh to T-Spline Conversion*, in "EG/ACM Symposium on Geometry Processing, 2006-06-26", Italy, 2006, http://hal.inria.fr/inria-00105611/en/.

[24] B. Lévy, S. Petitjean, N. Ray, J. Maillot.*Least Squares Conformal Maps for Automatic Texture Atlas Generation*, in "SIGGRAPH", ACM, Jul 2002.

[25] S. Meshkat, D. Talmor.*Generating a mixed mesh of hexahedra, pentahedra and tetrahedra from an underlying tetrahedral mesh*, in "International Journal for Numerical Methods in Engineering", 2000, vol. 49, n° 1-2, p. 17–30, http://dx.doi.org/10.1002/1097-0207(20000910/20)49:1/2<17::AID-NME920>3.0.CO;2-U.

[26] N. Ray, W. C. Li, B. Lévy, A. Sheffer, P. Alliez.*Periodic Global Parameterization*, in "ACM Transaction on Graphics", 2006, http://hal.inria.fr/inria-00104853/en/.

[27] N. Ray, V. Nivoliers, S. Lefebvre, B. Lévy.*Invisible Seams*, in "EUROGRAPHICS Symposium on Rendering Conference Proceedings", J. Lawrence, M. Stamminger (editors), Eurographics Association, 2010.

[28] M. A. Sabin.*Two open questions relating to subdivision*, in "Computing", 2009, vol. 86, n° 2-3, p. 213–217, http://dx.doi.org/10.1007/s00607-009-0059-2.

[29] P. Schroeder.*Wavelet Methods for Global Illumination*, Princeton University, 1994.

[30] G. Taubin.*A Signal processing approach to fair surface design*, in "SIGGRAPH Conference Proceedings", ACM, 1995, p. 351–358.

[31] S.-Q. Xin, B. Lévy, Z. Chen, L. Chu, Y. Yu, C. Tu, W. Wang.*Centroidal Power Diagrams with Capacity Constraints: Computation, Applications, and Extension*, in "ACM Trans. Graph.", November 2016, vol. 35, n° 6, p. 244:1–244:12, http://doi.acm.org/10.1145/2980179.2982428.

Project-Team BIGS

Biology, genetics and statistics

IN COLLABORATION WITH: Institut Elie Cartan de Lorraine (IECL)

IN PARTNERSHIP WITH:
CNRS

Université de Lorraine

RESEARCH CENTER
Nancy - Grand Est

THEME
Computational Biology

Table of contents

Project-Team BIGS

Creation of the Team: 2009 January 01, updated into Project-Team: 2011 January 01

Keywords:

Computer Science and Digital Science:

3. - Data and knowledge
3.1. - Data
3.1.1. - Modeling, representation
3.2. - Knowledge
3.2.3. - Inference
3.3. - Data and knowledge analysis
3.3.1. - On-line analytical processing
3.3.2. - Data mining
3.3.3. - Big data analysis
3.4.1. - Supervised learning
3.4.2. - Unsupervised learning
3.4.4. - Optimization and learning
3.4.7. - Kernel methods
3.5. - Social networks
3.5.1. - Analysis of large graphs
4.9.1. - Intrusion detection
6. - Modeling, simulation and control
6.1. - Mathematical Modeling
6.1.2. - Stochastic Modeling (SPDE, SDE)
6.2. - Scientific Computing, Numerical Analysis & Optimization
6.2.3. - Probabilistic methods
6.2.4. - Statistical methods
6.4. - Automatic control
6.4.2. - Stochastic control

Other Research Topics and Application Domains:

1. - Life sciences
1.1. - Biology
1.1.2. - Molecular biology
1.1.3. - Cellular biology
1.1.6. - Genomics
1.1.11. - Systems biology
1.1.13. - Plant Biology
1.2. - Ecology
1.4. - Pathologies
2.2. - Physiology and diseases
2.2.1. - Cardiovascular and respiratory diseases
2.2.3. - Cancer

2.3. - Epidemiology
2.4. - Therapies
5.5. - Materials
9. - Society and Knowledge
9.1. - Education

1. Members

Research Scientists
Romain Azaïs [Inria, Researcher]
Bruno Scherrer [Inria, Researcher, HDR]

Faculty Members
Anne Gégout Petit [Team leader, Univ. Lorraine, Professor, HDR]
Thierry Bastogne [Univ. Lorraine, Professor, HDR]
Sandie Ferrigno [Univ. Lorraine, Associate Professor]
Sophie Mezieres [Univ. Lorraine, Associate Professor]
Jean Marie Monnez [Univ. Lorraine, Professor, HDR]
Aurélie Muller-Gueudin [Univ. Lorraine, Associate Professor]
Pierre Vallois [Univ. Lorraine, Professor, HDR]
Yann Petot [Univ. Lorraine, PhD Student, Associate Professor until Sep 2017]

PhD Students
Lévy Batista [Cybernano, Univ. Lorraine]
Kévin Duarte [CHU Nancy]
Florine Greciet [SAFRAN, from Apr 2016, granted by CIFRE]
Clémence Karmann [Inria, from Oct 2016]
Pauline Guyot [Hôpital Virtuel de Lorraine, from Nov 2016]

Post-Doctoral Fellow
Florian Bouguet [Inria, from Sep 2016]

Visiting Scientists
Céline Lacaux [Univ. Avignon, Professor, HDR]
Samy Tindel [Purdue University, Professor, HDR]

Administrative Assistant
Céline Simon [Inria]

Other
Yaojie Shi [Inria, Internship, from Mar 2016 until Sep 2016]

2. Overall Objectives

2.1. Overall Objectives

BIGS is a team common to Inria, CNRS and Université de Lorraine, via the Institut Élie Cartan (UMR 7502 CNRS-Inria-UL). Our research is mainly focused on stochastic modeling and statistics for a methodological purpose but also aiming at a better understanding of biological systems. BIGS is composed of applied mathematicians whose research interests mainly concern probability and statistics. More precisely, our attention is directed on (1) stochastic modeling, (2) estimation and control for stochastic processes, (3) algorithms and estimation for graph data and (4) regression and machine learning. The main objective of BIGS is to exploit these skills in applied mathematics to provide a better understanding of some issues arising in life sciences, with a special focus on (1) tumor growth, (2) photodynamic therapy, (3) genomic data and micro-organisms population study, (4) epidemiology and e-health and (5) dynamics of telomeres. Each of these items will be detailed in the sequel.

3. Research Program

3.1. Introduction

We give here the main lines of our research that belongs to the domains of probability and statistics. For a better understanding, we made the choice to structure them in four items. Although this choice was not arbitrary, the outlines between these items are sometimes fuzzy because each of them deals with modeling and inference and they are all interconnected.

3.2. Stochastic modeling

Our aim is to propose relevant stochastic frameworks for the modeling and the understanding of biological systems. The stochastic processes are particularly suitable for this purpose. Among them, Markov chains give a first framework for the modeling of population of cells [105], [69]. Piecewise deterministic processes are non diffusion processes also frequently used in the biological context [53], [68], [61], [56]. Among Markov model, we also developed strong expertise about processes derived from Brownian motion and Stochastic Differential Equations [94], [67], [96]. For instance, knowledge about Brownian or random walk excursions [104], [93] helps to analyse genetic sequences and to develop inference about it. However, nature provides us with many examples of systems such that the observed signal has a given Hölder regularity, which does not correspond to the one we might expect from a system driven by ordinary Brownian motion. This situation is commonly handled by noisy equations driven by Gaussian processes such as fractional Brownian motion or (in higher dimensions of the parameter) fractional fields. The basic aspects of these differential equations are now well understood, mainly thanks to the so-called *rough paths* tools [80], but also invoking the Russo-Vallois integration techniques [95]. The specific issue of Volterra equations driven by fBm, which is central for the subdiffusion within proteins problem, is addressed in [54]. Many generalizations (Gaussian or not) of this model have been recently proposed, see for instance [44] for some Gaussian locally self-similar fields, [73] for some non-Gaussian models, [47] for anisotropic models. Our team has thus contributed [52], [74], [73], [75], [87] and still contributes [46], [48], [47], [76], [64] to this theoretical study: Hölder continuity, fractal dimensions, existence and uniqueness results for differential equations, study of the laws to quote a few examples. On the other hand, because of the observation of longitudinal data for each subject in medicine, we have to care about the random effect due to the subject and to choose adapted models like mixed effect models [77], [42], [43]. In the context of health-care and cost-effectiveness analysis, we are also interested in model of aggregation of different criteria. For this purpose, we develop research about fuzzy binary measures and Choquet integral [63], [81].

3.3. Estimation and control for stochastic processes

When one desires to confront theoretical probabilistic models with real data, statistical tools and control of the dynamics are obviously crucial. As matter of course, we develop inference about stochastic processes that we use for modeling, it is the heart of some of our projects. Control of stochastic processes is also a way to optimise administration (dose, frequency) of therapy.

The monograph [72] is a good reference on the basic estimation techniques for diffusion processes. Some attention has been paid recently to the estimation of the coefficients of fractional or multifractional Brownian motion according to a set of observations. Let us quote for instance the nice surveys [40], [51]. On the other hand, the inference problem for diffusions driven by a fractional Brownian motion has been in its infancy. A good reference on the question is [103], dealing with some very particular families of equations, which do not cover the cases of interest for us. We also recently proposed least-square estimators for these kind of processes [50], [88]. Inference about PDMP is also a recent subject that we want to develop. Our team has a good expertise about inference of the rate jump and the kernel of PDMP [38], [39], [37], [2]. However, there are many directions to go further into. For instance, previous works made the assumption of a complete observation of jumps and mode, that is unrealistic in practice. We want to tackle the problem of inference of "Hidden PDMP". It could be also interesting to investigate estimation followed by optimal control for ergodic PDMP. About pharmacokinetics modeling inference, several papers have been reported for the application of system identification techniques. But two issues were ignored in these previous works: presence of timing noise and identification from longitudinal data. In [41], we have proposed a bounded-error estimation algorithm based on interval analysis to solve the parameter estimation problem while taking into consideration uncertainty on observation time instants. Statistical inference from longitudinal data based on mixed effects models [77] can be performed by the *Monolix* software (http://lixoft.com/products/monolix/) developed by the Monolix group chaired by Marc Lavielle and France Mentré, and supported by Inria. We used it to estimate tumor growth in [42].

We consider the control of stochastic processes within the framework of Markov Decision Processes [90] and their generalization known as multi-player stochastic games [102], with a particular focus on infinite-horizon problems. In this context, we are interested in the complexity analysis of standard algorithms, as well as the proposition and analysis of numerical approximate schemes for large problems in the spirit of [45]. Regarding complexity, a central topic of research is the analysis of the Policy Iteration algorithm, which has made significant progress in the last years [108], [89], [66], [57], [101], but is still not fully understood. For large problems, we have a long experience of sensitivity analysis of approximate dynamic programming algorithms for Markov Decision Processes [99], [98], [100], [79], [97], and we currently investigate whether/how similar ideas may be adapted to multi-player stochastic games.

3.4. Algorithms and estimation for graph data

A graph data structure consists of a set of nodes, together with a set of (either unordered or ordered) pairs of these nodes called edges. This type of data is frequently used in various domains of application (in particular in biology) because they provide a mathematical representation of many concepts such as physical or biological structures and networks of relationship in a population. Some attention has recently been focused in the group on modeling and inference for graph data.

Suppose that we know the value of p variables on n subjects (in many applications, we have $n \ll p$). Inference network consists in evaluating the link between two variables knowing the others. [106] gives a very good introduction and many references about network inference and mining. Gaussian Graphical model is a convenient framework to infer network between quantitative variables: there is a edge between two variables if the partial correlation between them is non zero. So the problem is to compute the partial correlations trough the concentration matrix. Many methods are available to infer and test partial correlations in the context $n \ll p$ [106], [82], [60], [62]. However, when dealing with abundance data, because inflated zero data, data are far from gaussian assumption. Some authors work only with the binary "presence-absence" indicator via log-linear [65]. Models for inflated zero variables are not used for network inference and we want to develop them.

Among graphs, trees play a special role because they offer a good model for many biological concepts, from RNA to phylogenetic trees through plant structures. Our research deals with several aspects of tree data. In particular, we work on statistical inference for this type of data under a given stochastic model (critical Galton-Watson trees for example): in this context, the structure of the tree depends on an integer-valued distribution that we estimate from the observation of either only one tree, or a forest. We also work on lossy compression of trees via linear directed acyclic graphs. These methods make us able to compute distances between tree data faster than from the original structures and with a high accuracy. These results are valuable in the context of very large trees arising for instance in biology of plants.

3.5. Regression and machine learning

Regression models or machine learning aim at inferring statistical links between a variable of interest and covariates. It also aims at clustering subjects or variables in set homogeneous sets. In biological study, it is always important to develop adapted learning methods both in the context of "standard" data and also for very massive or online data.

A first approach for regression of quantitative variable is the non-parametric estimation of its cumulative distribution function. Many methods are available to estimate conditional quantiles and test dependencies [86], [70]. Among them we have developped nonparametric estimation trough local analysis via polynomial [58], [59] and we want to study properties of this estimator in order to derive measure of risk like confidence band and test. We study also many other regression models like survival analysis, spatio temporal models with covariates. Among the multiple regression models, we want to test, thanks to simulation methods, validity of their assumptions. Tests of this kind are called omnibus test. An omnibus test is an overall test that examines several assumptions together, the most known omnibus test is the one for testing gaussianity (that examines both skewness and kurtosis [55]).

As it concerns the analysis point of high dimensional data, our view on the topic relies on the so-called *French data analysis school*, and more specifically on Factorial Analysis tools. In this context, stochastic approximation is an essential tool (see Lebart's paper [78]), which allows one to approximate eigenvectors in a stepwise manner. A systematic study of Principal Component and Factorial Analysis has then been lead by Monnez in the series of papers [85], [83], [84], in which many aspects of convergences of online processes are analyzed thanks to the stochastic approximation techniques. BIGS aims at performing accurate classification or clustering by taking advantage of the possibility of updating the information "online" using stochastic approximation algorithms [71]. We focus on several incremental procedures for regression and data analysis like linear and logistic regressions and PCA. We also focus the biological context of high-throughput bioassays in which several hundreds or thousands of biological signals are measured for a posterior analysis. The inference of the modeling conclusions from a sample of wells to the whole population requires to account for the inter-individual variability within the modeling procedure. One solution consists in using mixed effects models but up to now no similar approach exists in the field of dynamical system identification. As a consequence, we aim at developing a new solution based on an ARX (Auto Regressive model with eXternal inputs) model structure using the EM (Expectation-Maximisation) algorithm for the estimation of the model parameters.

4. Application Domains

4.1. Tumor growth

Cancer is the result of inter-dependent multi-scale phenomena and this is mainly why the understanding of its spread is still an unsolved problem. In integrative biology, mathematical models play a central role; they help biologists and clinicians to answer complex questions through numerical simulations and statistical analyses. The main issue here is to better understand and describe the role of cell damage heterogeneity and associated mutant cell phenotypes in the therapeutic responses of cancer cell populations submitted to a radiotherapy sessions during *in vitro* experiments. The cell heterogeneity is often described as randomness in mathematical modeling and different representations, such as Markov chains, branching processes and even stochastic differential equations, have been recently used.

4.2. Photodynamic therapy

Since 1988, some control system scientists and biologists at the CRAN [0] have worked together to develop the photodynamic therapy (PDT in the sequel), an alternative treatment for cancer, by means of a model-based approach. The global aim in this direction is to use statistical as well as mechanistic models in order to improve the response reproducibility, help biologists and chemists in the design of new photosensitizing agents and provide insight into complex phenomena associated with oncogenesis, tumor angiogenesis and interactions with the treatment. This heavily relies on the production of accurate and simple enough models involving various type of stochastic processes, such as Markov chains, branching processes and stochastic differential equations. The main questions here concern generally identification or estimation properties, but simulation issues can be important too.

[0] Centre de Recherche en Automatique de Nancy, http://www.cran.uhp-nancy.fr/francais/themes_rech/sbs/beam/index.php

4.3. Genomic data and micro-organisms population study

Generation genomic technologies allow clinicians and biomedical researchers to drastically increase the amount of genomic data collected on large cohort of patients and populations. We want to contribute to a better understanding of the correlations between gene trough their expression data, of the structure of ARN and of the genetic bases of drug response and disease and to detect significant sequences characterizing a gene. For instance the biopharmaceutical company Transgene has recently contacted us to analyse their genomic and proteomic data particularly for the purpose to find markers of the success of therapies that they develop against cancer.

Network inference has also applications for the analysis of micro-organisms population, that we apply to micro-organism inside and around the truffle trough a collaboration with INRA Nancy. We want also study other specific complex microbial communities like that found at tree roots in order to characterize phenotype of the tree. There is also application in human health (for instance identification of network between bacteria inside colon).

4.4. Epidemiology and e-health

Trough J.-M. Monnez and his collaborator Pr E. Albuisson, BIGS is stakeholder of projects with University Hospital of Nancy that is FHU CARTAGE (Fédération Hospitalo Universitaire Cardial and ARTerial AGEing; leader: Pr Athanase BENETOS), RHU Fight HF (Fighting Heart Failure; leader: Pr Patrick ROSSIGNOL), and "Handle your heart", team responsible for the creation of a drug prescription support software for the treatment of heart failure. All these projects are in the context of personalized medicine and deal with biomarkers research; prognostic value of quantitative variables and events and scoring of heart failure. Other collaborations with clinicians concern foetopathology and cancer again.

4.5. Dynamics of telomeres

A telomere is a region of repetitive and non coding nucleotide sequences at each end of a chromosome. The telomeres are disposable buffers at the ends of chromosomes which are truncated during cell division; so that, over time, due to each cell division, the telomere ends become shorter. By this way, they are markers of aging. Mathematical modeling of telomere dynamics is recent [36], [107], [91], [49]. Trough a collaboration with Pr A. Benetos, geriatrician at CHU Nancy, and some members of Inria team TOSCA, we want to work in three connected directions: (1) propose a dynamical model for the lengths of telomeres and study its mathematical properties (long term behavior of the distribution of lengths, quasi-stationarity, etc); (2) use these properties to develop new statistical methods for estimating the various parameters; and (3) find and use a suitable methodology for the analysis of the available data (Pr Benetos) for instance for the study of the length distribution for a subject and its evolution.

5. Highlights of the Year

5.1. Highlights of the Year

BIGS team has organised a two-days workshop "Rencontres des équipes Inria travaillant sur le cancer" that took place Paris in March. 10 inria teams were present. The program is available on https://team.inria.fr/bigs/workshopcancer/.

6. New Software and Platforms

6.1. AGH

KEYWORDS: statistical analysis, ordered trees

SCIENTIFIC DESCRIPTION

The Matlab toolbox AGH provides methods for statistical analysis of ordered trees from their Harris paths in a user-friendly environment. More precisely it allows to easily compute estimators of the relative scale of trees which share the same shape. These estimators have been introduced for Galton-Watson trees conditioned on their number of nodes but may be computed for any ordered tree. The theoretical study of these estimators is presented in the associated paper [30] which should be consulted in parallel.

FUNCTIONAL DESCRIPTION

The Matlab toolbox AGH provides methods for statistical analysis of ordered trees from their Harris paths in a user-friendly environment.

- Participants: Romain Azaïs, Alexandre Genadot, Benoît Henry
- Contact: romain.azais@inria.fr
- URL: http://agh.gforge.inria.fr

7. New Results

7.1. Stochastic modeling

7.1.1. Spatial and spatio-temporal modeling

Participants: A. Gégout-Petit
External collaborators: Y. Cao, S. Li, L. Guerin-Dubrana (Inra Bordeaux)

In the framework of a collaboration with INRA Bordeaux about the esca-illness of vines, Anne Gégout-Petit with Shuxian Li developed different spatial models and spatio-temporal models for different purposes: (1) study the distribution and the dynamics of esca vines in order to tackle the aggregation and the potential spread of the illness (2) propose a spatio-temporal model in order to capture the dynamics of cases and measure the effects of environmental covariates. For purpose (1), we propose different test based on the join count statistics, a paper is accepted for publication [5]. We also developped a two-step centered autologistic model for the study of the dynamic of propagation. This work has been presented as invited paper in [20] and is in preparation for publication.

7.1.2. Modelisation of response to chemotherapy in gliomas

Participant: S. Wantz-Mézières
External collaborator: J.-M. Moureaux, Y. Gaudeau, M. Ben Abdallah, M. Ouqamra (CRAN, Université de Lorraine), L. Taillandier, M. Blonski (CHU Nancy)
The collaboration with neurologists (CHU Nancy) and automaticians (CRAN) has carried on this year and led to the PhD presentation of M. Ben Abdallah, on December 12, 2016 [17], [16]. We completed the modeling approach by a data analysis one. In the framework of a master 2 project, supervised and non supervised methods have confirmed our results on our local data base. This encourages us to continue our work in extending the data base via a collaboration with Montpellier CHU. Our perspectives are to validate multi-factor models, including biological and anatomopathological factors, and to design a decision-aid tool for praticians.

7.1.3. Time-changed extremal process as a random sup measure

Participant: Céline Lacaux
External collaborator: Gennady Samorodnistky

In extreme value theory, one of the major topics is the study of the limiting behavior of the partial maxima of a stationary sequence. When this sequence is i.i.d., the unique limiting process is well-known and called the extremal process. Considering a long memory stable sequence, the limiting process is obtained as a simple power time change extremal process. Céline Lacaux and Gennady Samorodnistky have proved that this limiting process can also be interpreted as a restriction of a self-affine random sup measure. In addition, they have established that this random measure arises as a limit of the partial maxima of the same long memory stable sequence, but in a different space. Their results open the way to propose new self-similar processes with stationary max-increments.

7.1.4. Fast and Exact synthesis of some operator scaling Gaussian random fields

Participant: Céline Lacaux

External collaborator: Hermine Biermé

Operator scaling Gaussian random fields, as anisotropic generalizations of self-similar fields, know an increasing interest in the literature. Up to now, such models were only defined through stochastic integrals, without knowing explicitly their covariance functions. In link with this misunderstanding, one of the drawbacks is that no exact method of simulation has been proposed. In view to fill this lack, Hermine Biermé and Céline Lacaux have recently exhibit explicit covariance functions, as anisotropic generalizations of fractional Brownian fields ones. This allows them to propose a fast and exact method to synthetise an operator scaling Gaussian random fields with such a covariance function. Their algorithm is based on the famous circulant embedding matrix method. This is a first piece of work to popularized operator scaling Gaussian random field in anisotropic spatial data modeling.

7.1.5. DNA sequences analysis

Participants: P. Vallois

External collaborators: A. Lagnoux and S. Mercier (Toulouse)

In an article accepted at Bioinformatics, the goal is to illustrate different results on the local score distribution assuming an i.i.d. model, especially the one based on the pair (local score,length) and the one on the local score position. We measure with statistical tests how different approximations of the local score distribution fit to simulated sequences. In particular, our simulations show that the popular Karlin & Altschul approximation is not accurate in a wide range of situations. We add to the local score the length of the segment that realises it and we study the induced changes with numerical simulations. We also study specificity and sensitivity for the different methods. We introduce a new one dimensional statistic which is a function of H_n^* and L_n^* and we test its distribution. Finally, we estimate the probability that $H_n^* = H_n$ in different settings.

7.2. Estimation and control for stochastic processes

7.2.1. Piecewise-deterministic Markov processes

Participants: Romain Azaïs, Florian Bouguet, Anne Gégout-Petit, Florine Greciet, Aurélie Muller-Gueudin

External participants: Michel Benaïm (Université de Neuchâtel), Bertrand Cloez (Inra-SupAgro MISTEA), Alexandre Genadot (Inria CQFD, Université de Bordeaux)

A piecewise-deterministic Markov process is a stochastic process whose behavior is governed by an ordinary differential equation punctuated by random jumps occurring at random times. This class of stochastic processes offers a wide range of applications, especially in biology (kinetic diatery exposure model and growth of bacteria for example). BIGS' members mainly work on statistical inference techniques for these stochastic processes [2], [29], which is an essential step to build relevant application models. We also investigate the probabilistic properties of these processes [32], [31] as well as the application in reliability to crack growth in some alloy in the industrial context of the PhD thesis of Florine Greciet with SAFRAN Aircraft Engines [33].

In a preprint recently accepted for publication in Electronic Journal of Statistics [2], we focus on the nonparametric estimation problem of the jump rate for piecewise-deterministic Markov processes observed within a long time interval under an ergodicity condition. More precisely, we introduce an uncountable class (indexed by the deterministic flow) of recursive kernel estimates of the jump rate and we establish their strong pointwise consistency as well as their asymptotic normality. In addition, we propose to choose among this class the estimator with the minimal variance, which is unfortunately unknown and thus remains to be estimated. We also discuss the choice of the bandwidth parameters by cross-validation methods. In [29], we state a new characterization of the jump rate when the transition kernel only charges a discrete subset of the state space. We deduce from this result a competitive nonparametric technique for estimating this feature of interest. We state the uniform convergence in probability of the estimator. Both the methodologies have been illustrated on numerical examples and real data.

The article [32] deals with a class of conservative growth-fragmentation equations with a deterministic viewpoint. With the help of Foster-Lyapunov criteria, we study the long-time behavior of some associated piecewise-deterministic Markov process, which represents a typical individual following the dynamics of the equation. If the growth and the fragmentation are balanced, it is possible to provide existence and unicity for the stationary distribution on the process, as well as precise bounds for its tails of distributions in the neighborhoods of both 0 and $+\infty$. Our probabilistic results are systematically compared to estimates already obtained with deterministic methods.

In [31], we are interested by the long-time behavior of inhomogeneous-time Markov chains. We put forward an original and unified approach to relate some of their asymptotic properties (stationary distribution, speed of convergence, ...) to the ones of an auxiliary homogeneous-time Markov process. Such results are close to traditional functional limit theorems, but our method differs from the standard “Tightness/Identification” argument; it is based on the notion of asymptotic pseudotrajectories on the space of probability measures. We recover classical results, such as normalized bandit algorithms converging to a piecewise-deterministic Markov process, or weighted random walks or decreasing step Euler schemes approximated with solutions of stochastic differential equations.

7.2.2. Statistics of Markov chains

Participant: Romain Azaïs

External participants: Bernard Delyon (Université Rennes 1), François Portier (Télécom ParisTech)

Suppose that a mobile sensor describes a Markovian trajectory in the ambient space. At each time the sensor measures an attribute of interest, e.g., the temperature. Using only the location history of the sensor and the associated measurements, the aim of the paper [27] is to estimate the average value of the attribute over the space. In contrast to classical probabilistic integration methods, e.g., Monte Carlo, the proposed approach does not require any knowledge on the distribution of the sensor trajectory. Probabilistic bounds on the convergence rates of the estimator are established. These rates are better than the traditional “root n”-rate, where n is the sample size, attached to other probabilistic integration methods. For finite sample sizes, the good behaviour of the procedure is demonstrated through simulations and an application to the evaluation of the average temperature of oceans is considered.

7.2.3. Realtime Tracking of the Photobleaching Trajectory during Photodynamic Therapy

Participant: T. Bastogne

Photodynamic therapy (PDT) is an alternative treatment for cancer that involves the administration of a photosensitizing agent, which is activated by light at a specific wavelength. This illumination causes after a sequence of photoreactions, the production of reactive oxygen species responsible for the death of the tumor cells but also the degradation of the photosensitizing agent, which then loose the fluorescence properties. The phenomenon is commonly known as photobleaching process and can be considered as a therapy efficiency indicator. In [8], we present the design and validation of a real time controller able to track a preset photobleaching trajectory by modulating the light impulses width during the treatment sessions. This innovative solution was validated by in vivo experiments that have shown a significantly improvement of reproducibility of the inter-individual photobleaching kinetic. We believe that this approach could lead to personalized photodynamic therapy modalities in the near future.

7.2.4. Stochastic simulation and design of numerical experiments for the prediction of nanoparticles/X-ray interactions in radiotherapy.

Participant: T. Bastogne

The increase of computational environments dedicated to the simulation of nanoparticles (NP)-X-Rays interactions has opened new perspectives in computer-aided-design of nanostructured materials for biomedical applications. Several published studies have shown a crucial need of standardization of these numerical simulations [92]. That is why, we proposed to perform a robustness multivariate analysis in [8]. A gold nanoparticle (GNP) of 100 nm diameter was selected as a standard nano-system activated by a X-ray source placed just below the NP. Two response variables were examined: the dose enhancement in seven different spatial regions of interest around the NP and the duration of the experiments. 9 factors were pre-identified as potentially critical. A Plackett-Burman design of numerical experiments was applied to estimate and test the effects of each simulation factors on the examined responses. Four factors: the working volume, the spatial resolution, the spatial cutoff and the computational mode (parallelization) do not significantly affect the dose deposition results and none except the last one may reduce the computational duration. The energy cutoff may cause significant variations of the dose enhancement in some specific regions of interest: the higher the cutoff, the closer the secondary particles will stop from the GNP. By contrast, the Auger effect as well as the choice of the physical medium and the fluence level clearly appear as critical simulation parameters. Consequently, these four factors may be compulsory examined before comparing and interpreting any simulation results coming from different simulation sessions.

In [9], we address the prediction issue of organometallic nanoparticles (NPs)-based radiosensitization enhancement. The goal was to carry out computational experiments to quickly identify efficient nanostructures and then to preferentially select the most promising ones for the subsequent in vivo studies. To this aim, this interdisciplinary article introduces a new theoretical Monte Carlo computational ranking method and tests it using 3 different organometallic NPs in terms of size and composition. While the ranking predicted in a classical theoretical scenario did not fit the reference results at all, in contrast, we showed for the first time how our accelerated in silico virtual screening method, based on basic in vitro experimental data (which takes into account the NPs cell biodistribution), was able to predict a relevant ranking in accordance with in vitro clonogenic efficiency. This corroborates the pertinence of such a prior ranking method that could speed up the preclinical development of NPs in radiation therapy.

This in-silico approach was tested in [25] to screen radiosensitizing nanoparticles and the results have been validated by in vitro assays.

7.2.5. Complexity analysis of Policy Iteration

Participant: Bruno Scherrer

Given a Markov Decision Process (MDP) with n states and a total number m of actions, we study in [10] the number of iterations needed by Policy Iteration (PI) algorithms to converge to the optimal γ-discounted policy. We consider two variations of PI: Howard's PI that changes the actions in all states with a positive advantage, and Simplex-PI that only changes the action in the state with maximal advantage. We show that Howard's PI terminates after at most $O\left(\frac{m}{1-\gamma}\log\left(\frac{1}{1-\gamma}\right)\right)$ iterations, improving by a factor $O(\log n)$ a result by Hansen et al., while Simplex-PI terminates after at most $O\left(\frac{nm}{1-\gamma}\log\left(\frac{1}{1-\gamma}\right)\right)$ iterations, improving by a factor $O(\log n)$ a result by Ye. Under some structural properties of the MDP, we then consider bounds that are independent of the discount factor γ: quantities of interest are bounds τ_t and τ_r—uniform on all states and policies—respectively on the *expected time spent in transient states* and *the inverse of the frequency of visits in recurrent states* given that the process starts from the uniform distribution. Indeed, we show that Simplex-PI terminates after at most $\widetilde{O}\left(n^3m^2\tau_t\tau_r\right)$ iterations. This extends a recent result for deterministic MDPs by Post & Ye, in which $\tau_t \leq 1$ and $\tau_r \leq n$; in particular it shows that Simplex-PI is strongly polynomial for a much larger class of MDPs. We explain why similar results seem hard to derive for Howard's PI. Finally, under the additional (restrictive) assumption that the state space is partitioned in two sets, respectively states that are transient and recurrent for all policies, we show that both Howard's PI and Simplex-PI terminate after at most $\widetilde{O}(m(n^2\tau_t + n\tau_r))$ iterations.

7.2.6. Approximate Dynamic Programming for Markov Games

Participant: Bruno Scherrer

We have made two contributions to the analysis of Approximate Dynamic Programming algorithms for Markov Games.

First, we extend in [21] several non-stationary Reinforcement Learning (RL) algorithms and their theoretical guarantees to the case of discounted zero-sum Markov Games (MGs). As in the case of Markov Decision Processes (MDPs), non-stationary algorithms are shown to exhibit better performance bounds compared to their stationary counterparts. The obtained bounds are generically composed of three terms: 1) a dependency over gamma (discount factor), 2) a concentrability coefficient and 3) a propagation error term. This error, depending on the algorithm, can be caused by a regression step, a policy evaluation step or a best-response evaluation step. As a second contribution, we empirically demonstrate, on generic MGs (called Garnets), that non-stationary algorithms outperform their stationary counterparts. In addition, it is shown that their performance mostly depends on the nature of the propagation error. Indeed, algorithms where the error is due to the evaluation of a best-response are penalized (even if they exhibit better concentrability coefficients and dependencies on gamma) compared to those suffering from a regression error.

Furthermore, we report in [22] theoretical and empirical investigations on the use of quasi-Newton methods to minimize the Optimal Bellman Residual (OBR) of zero-sum two-player Markov Games. First, it reveals that state-of-the-art algorithms can be derived by the direct application of Newton's method to different norms of the OBR. More precisely, when applied to the norm of the OBR, Newton's method results in the Bellman Residual Minimization Policy Iteration (BRMPI) and, when applied to the norm of the Projected OBR (POBR), it results into the standard Least Squares Policy Iteration (LSPI) algorithm. Consequently, new algorithms are proposed, making use of quasi-Newton methods to minimize the OBR and the POBR so as to take benefit of enhanced empirical performances at low cost. Indeed, using a quasi-Newton method approach introduces slight modifications in term of coding of LSPI and BRMPI but improves significantly both the stability and the performance of those algorithms. These phenomena are illustrated on an experiment conducted on artificially constructed games called Garnets.

7.3. Algorithms and estimation for graph data

7.3.1. Modelisation of networks of multiagent systems

Participants: Aurélie Muller-Gueudin

We relate here a collaboration with researchers in Automatic in Nancy (CRAN).

We consider here networks, modeled as a graph with nodes and edges representing the agents and their interconnections, respectively. The connectivity of the network, persistence of links and interactions reciprocity influence the convergence speed towards a consensus.

The problem of consensus or synchronization is motivated by different applications as communication networks, power and transport grids, decentralized computing networks, and social or biological networks.

We then consider networks of interconnected dynamical systems, called agents, that are partitioned into several clusters. Most of the agents can only update their state in a continuous way using only inner-cluster agent states. On top of this, few agents also have the peculiarity to rarely update their states in a discrete way by reseting it using states from agents outside their clusters. In social networks, the opinion of each individual evolves by taking into account the opinions of the members belonging to its community. Nevertheless, one or several individuals can change its opinion by interacting with individuals outside its community. These inter-cluster interactions can be seen as resets of the opinions. This leads us to a network dynamics that is expressed in term of reset systems. We suppose that the reset instants arrive stochastically following a Poisson renewal process.

We have an accepted paper in the journal IEEE Transactions on Automatic Control [6].

7.3.2. Compression and analysis of trees

Participant: Romain Azaïs

External participants: Jean-Baptiste Durand (ENSIMAG, Inria MISTIS), Christophe Godin (Inria Virtual Plants), Benoît Henry (Inria TOSCA puis Madynes), Alexandre Genadot (Université de Bordeaux, Inria CQFD)
Tree-structured data naturally appear in various fields, particularly in biology where plants and blood vessels may be described by trees, but also in computer science because XML documents form a tree structure. Among trees, the class of self-nested trees presents remarkable compression properties because of the systematic repetition of subtrees in their structure. In a recent preprint [28], we provide a better combinatorial characterization of this specific family of trees. We show that self-nested trees may be considered as a good approximation class of unordered trees. In addition, we compare our approximation algorithms with a competitive approach of the literature on a simulated dataset. On the other hand, the paper [30] is devoted to the estimation of the relative scale of ordered trees that share the same layout. The theoretical study is achieved for the stochastic model of conditioned Galton-Watson trees. New estimators are introduced and their consistency is stated. A comparison is made with an existing approach of the literature. A simulation study shows the good behavior of our procedure on finite-sample sizes. An application to the analysis of revisions of Wikipedia articles is also considered through real data.

7.4. Regression and machine learning

7.4.1. Aggregated methods for covariates selection in high-dimensional data under dependence

Participants: A. Gégout-Petit, A. Muller-Gueudin, Y. Shi
External collaborators: B. Bastien (Transgene, Strasbourg)

In the purpose to select factors linked to the efficiency of a treatment in the context of high dimension (about 100.000 covariates), we have developed a new methodology to select and rank covariates associated to a variable of interest in a context of high-dimensional data under dependence but few observations. The methodology imbricates successively rough selection, clustering of variables, decorrelation of variables using Factor Latent Analysis, selection using aggregation of adapted methods and finally ranking through bootstrap replications. Simulations study shows the interest of the decorrelation inside the different clusters of covariates. The methodology was applied to select covariates among genomics, proteomics covariates linked to the success of a immunotherapy treatment for the lung cancer. A paper on the subject is in preparation.

7.4.2. Clustering of the values of a response variable and simultaneous covariate selection using a stepwise algorithm

Participant: J.-M. Monnez
External collaborator: O. Collignon (LIH Luxembourg)
In supervised learning the number of values of a response variable to predict can be very high. Grouping these values in a few clusters can be useful to perform accurate supervised classification analyses. On the other hand selecting relevant covariates is a crucial step to build robust and efficient prediction models. We propose in this paper an algorithm that simultaneously groups the values of a response variable into a limited number of clusters and selects stepwise the best covariates that discriminate this clustering. These objectives are achieved by alternate optimization of a user-defined selection criterion. This process extends a former version of the algorithm to a more general framework. Moreover possible further developments are discussed in detail [3].

7.4.3. Death or hospitalization scoring for heart failure patients

Participant: J.-M. Monnez, K. Duarte
External collaborator: E. Albuisson (CHU, Nancy)
The purpose of this study was to define a short term event (death or hospitalization) score for heart failure patients based on the observation of biological, clinical and medical historical variables. Some of them were transformed or winsorized. Two methods of statistical learning were performed, logistic regression and linear discriminant analysis, different variable selection methods were used, on bootstrap samples. Aggregation of classifiers and out-of-bag validation were used. Finally a score taking values between 0 and 100 was established and an odds-ratio was defined in order to support medical decision (writing in progress).

7.4.4. *Sequential linear regression with online standardized data*

Participant: J.-M. Monnez, K. Duarte

External collaborator: E. Albuisson

We consider the problem of sequential least square multidimensional linear regression using a stochastic approximation process. The choice of the stepsize may be crucial in this type of process. In order to avoid the risk of numerical explosion which can be encountered, we define three processes with a variable or a constant stepsize and establish their convergence. Finally these processes are compared to classic processes on 11 datasets, 6 with a continuous output and 5 with a binary output, for a fixed total number of observations used and then for a fixed processing time. It appears that the third-defined process with a very simple choice of the stepsize gives usually the best results (paper to be submitted).

7.4.5. *Mixed-effects ARX Model Identification of Dynamical Biological Systems*

Participants: T. Bastogne, L. Batista

System identification is a data-driven modeling approach more and more used in biology and biomedicine [26]. In this application context, each assay is always repeated to estimate the response variability. The inference of the modeling conclusions to the whole population requires to account for the inter-individual variability within the modeling procedure. One solution consists in using mixed effects models but up to now no similar approach exists in the field of dynamical system identification. In [23], we propose a new solution based on an ARX (Auto Regressive model with eXternal inputs) structure using the EM (Expectation-Maximisation) algorithm for the estimation of the model parameters. Simulations show the relevance of this solution compared with a classical procedure of system identification repeated for each subject.

In [24], we propose a solution to firstly estimate the Fisher information matrix using the Louis' method and secondly to determine the parameters confidence intervals of an ARX model structure. We show relevance of the proposed solution in simulation and using real in-vitro data coming from realtime cell impedance measurements.

In parallel, we applied the mixed-effect modeling approach to the analysis in vivo responses in order to identify pronostic biomarkers of tumor regrowth after photodynamic therapy [11]. This application corroborated the practical relevance of our model-based approach.

7.4.6. *Uniform asymptotic certainty bands for the conditional cumulative distribution function*

Participants: S.Ferrigno, A. Muller-Gueudin, M. Maumy-Bertrand (IRMA, Strasbourg)

In this work, we study the conditional cumulative distribution function and a nonparametric estimator associated to this function. The conditional cumulative distribution function has the advantages of completely characterizing the law of the random considered variable, allowing to obtain the regression function, the density function, the moments and the conditional quantile function. As a nonparametric estimator of this function, we focus on local polynomial techniques described in Fan and Gijbels [ref]. In particular, we use the local linear estimation of the conditional cumulative distribution function.

The objective of this work is to establish uniform asymptotic certainty bands for the conditional cumulative distribution function. To this aim, we give exact rate of strong uniform consistency for the local linear estimator of this function (writing in progress).

7.4.7. *Omnibus tests for regression models*

Participants: R.Azaïs, S.Ferrigno, M-J Martinez Marcoux (LJK, Grenoble)

The aim of this collaboration begins is to compare, through simulations, several methods to test the validity of a regression model. These tests can be "directional" in that they are designed to detect departures from mainly one given assumption of the model (for example the regression function, the variance or the error) or global (for example the conditional distribution function). The establishment of such statistical tests require the use of nonparametric estimators various functions (regression, variance, cumulative distribution function). The idea would then be able to build a tool (package R) that allows a user to test the validity of the model it uses through different methods and varying parameters associated with modeling. This work is currently in progress.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. Bilateral Contracts with Industry

8.1.1.1. Transgene 1. (2016-2017)

Participants: A. Gégout-Petit, A. Muller-Gueudin, Y. Shi
Transgene (Euronext: TNG), part of Institut Mérieux, is a publicly traded French biopharmaceutical company focused on discovering and developing targeted immunotherapies for the treatment of cancer and infectious diseases. B. Bastien, head of the biostatistics team appeals to BIGS to select covariates among genomics, proteomics expressions linked to the success of a treatment of the lung cancer. This subject was the purpose of the master thesis of Y. Shi and a paper on the subject is in preparation.

8.1.1.2. Transgene 2. (2016-2017)

Participants: T. Bastogne, L. Batista, P. Vallois
Transgene (Euronext: TNG), part of Institut Mérieux, is a publicly traded French biopharmaceutical company focused on discovering and developing targeted immunotherapies for the treatment of cancer and infectious diseases. B. Bastien, head of the biostatistics team appeals to BIGS to model data collected in vivo for growth tumor and to measure the effect of the treatment on the dynamics of the tumor.

8.1.1.3. SAFRAN Aircraft Engines (2016-2019)

Participants: R. Azaïs, A. Gégout-Petit, F. Greciet
SAFRAN Aircraft Engines designs and products Aircraft Engines. For the design of pieces, they have to understand mechanism of crack propagation under different conditions. It appeals to BIGS for modeling crack propagation with Piecewise Deterministic Markov Processes (PDMP). It is the subject of F. Greciet PhD, granted by ANRT. F. Greciet presented her work during a Fédération Charles Hermite Journey on November the 23th. She was laureat of "Mathématiques, oxygene du monde numérique" poster challenge [33].

9. Partnerships and Cooperations

9.1. National Initiatives

- *PEPS AMIES* (2016), Apprentissage supervisé pour l'aide au diagnostic, Collaboration Institut Elie Cartan avec la StartUp SD Innovation Frouard. Participants: A. Gégout-Petit, P. Vallois
- *Popart (2016-2017)* In the framework of collaboration with A. Deveau of Inra Nancy, A. Gégout-Petit and A. Muller-Gueudin are included in the Inra "Microbial Ecosystems & Metaomics, Call 2016" Project "Popart"for "Regulation of the Poplar microbiome by its host: is the immune system involved ? ". The aim is to develop methodology for the inference of regulation network betwen micro-organisms around Poplar. The specificity of the data is the inflation of zeros that has to be taken into account.
- *Intérêt des antiangiogènes dans la potentialisation des thérapies par rayonnement dans le cas des glioblastomes* (2016). Funding organism: Ligue contre le Cancer (CCIR-GE). Leader: N. Thomas (CRAN, U. Lorraine). Participants : C. Lacaux and A. Muller-Gueudin
- (2014-16), A library of Near-InfraRed absorbing photosensitizers: tailoring and assessing photo-physical and synergetic photodynamic properties, Funding organism: PHC Bosphore - Campus France, Leader: M. Barberi-Heyob (CRAN), Thierry Bastogne
- GDR 3475 Analyse Multifractale, Funding organism: CNRS, Leader: S. Jaffard (Université Paris-Est), Céline Lacaux

- GDR 3477 Géométrie stochastic, Funding organism: CNRS, Leader: P. Calka (Université Rouen), Céline Lacaux
- FHU CARTAGE (Fédération Hospitalo Universitaire Cardial and ARTerial AGEing ; leader : Pr Athanase BENETOS), Jean-Marie Monnez
- RHU Fight HF (Fighting Heart Failure ; leader : Pr Patrick ROSSIGNOL), located at the University Hospital of Nancy, Jean-Marie Monnez
- Project "Handle your heart", team responsible for the creation of a drug prescription support software for the treatment of heart failure, head: Jean-Marie Monnez

9.2. European Initiatives

9.2.1. Collaborations in European Programs, Except FP7 & H2020

- Photobrain project. AGuIX theranostic nanoparticles for vascular-targeted interstitial photodynamic therapy of brain tumors, project **EuroNanoMed II**, resp.: M. Barberi-Heyob, (2015-2017), participant: T. Bastogne.
- NanoBit Project. Nanoscintillator-Porphyrin Complexes for Bimodal RadioPhotoDynamic Therapy, project **EuroNanoMed II**, resp.: P. Juzenas, (2016-2018), participant: T. Bastogne.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

- BIGS team has organised a two-days workshop "Rencontres des équipes Inria travaillant sur le cancer" in Paris. 10 inria teams were present. https://team.inria.fr/bigs/workshopcancer/
- A. Gégout-Petit co-organised the "Health Session" of the day Fédération Charles Hermite- Enterprises, Nancy, January 2016.
- Céline Lacaux participated to the organisation of the following events:
  – European Study Group with Industry, 117th edition, May 2016, Avignon.
  – Session *Statistics* of the 14th Colloque Franco-Roumain de Mathématiques Appliquées, August 2016, Iasi.
  – Conference of GDR 3475 Analyse Multifractale, September 2016, Avignon.

10.1.2. Scientific Events Selection

10.1.2.1. Chair of Conference Program Committees

- A. Gégout-Petit is chair of 2017 "Congrès Francophone International de l'Enseignement de la Statistique" (CFIES), Grenoble, September, 2017.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

P. Vallois is in the editorial board of "Risk and Decision Analysis".

10.1.3.2. Reviewer - Reviewing Activities

All the BIGS members are regular reviewers for journals in probability, statistics and machine learning as: Bernoulli, Scandinavian Journal of statistics, Stochastics, Journal of Statistical Planning Inference, Journal of theoretical Biology, IEEE Trans. Biomedical Eng., Theoretical Biology and Medical Modelling, Royal Society of Chemistry, Signal Processing: Image Communication, Mathematical Biosciences, LIDA, Annals of Applied Probability, Annals of Operations Research and Journal of Machine Learning Research, as well as conferences such as ICML, World IFAC Congress, FOSBE, ALCOSP...

10.1.4. Invited Talks

- Anne Gégout-Petit was invited in SADA'2016 conference in Cotonou. [20]
- Bruno Scherrer was an invited speaker in EWRL'2016 workshop in Barcelona.
- Thierry Bastogne was invited the 19 October 2015 by Pr. Luc Leyns at the Vrije Universities Brussels for a talk on the *Statistical Analysis of Cell Impedance Signals for the Characterization of Anti-Cancer Drug Effects*.
- Romain Azaïs was an invited speaker in SSIAB 2016 in Rennes.
- S. Ferrigno : *Nouvelles approches d'estimation de la croissance en Foetopathologie*. Journée "Nouvelle approche de la croissance foetale", Maternité Régionale du CHRU de Nancy (Sept 2016).

10.1.5. Leadership within the Scientific Community

- Anne Gégout-Petit is member of the board of the European Regional Council of the Bernoulli society
- Céline Lacaux is responsible of the *Statistic team*, Laboratory of Mathematic of Avignon (since September 2016)

10.1.6. Scientific Expertise

- T. Bastogne: scientific expert in Biostatistics and Signal Processing in Nanomedicine for CYBER-nano (start-up).

10.1.7. Research Administration

- A. Gégout-Petit: elected member of the laboratory of mathematics "Institut Elie Cartan de Lorraine".
- Céline Lacaux is
  - member of the bord of the SMAI-MAS group,
  - elected member of the council of the Laboratory Mathematics of Avignon,
  - correspondant AMIES pour Avignon,
  - Member of the scientific committee of GDR 3477 Stochastic Geometry.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

- A. Gégout-Petit : Head of the Master 2 "Ingénierie Mathématique et Outils Informatiques (Mathematical Engineering and Computer Tools)", Université de Lorraine
- A. Gégout-Petit created and is now in charge of cursus CMI in applied mathematics for Lorraine University
- P. Vallois is head of the "Parcours Mathématiques Financières" of the master "Applied mathematics" of Université de Lorraine
- P. Vallois is head of the convention between "Université de Lorraine and Université Hammam Sousse" about master organization. Master ISC (Ingénierie de Systèmes Complexes)
- T. Bastogne is in charge of the spécialité Systèmes & TIC du master Ingénierie de Systèmes Complexes
- T. Bastogne created and is now in charge of professional master: CIIBLE (Cybernétique, Instrumentation, Image en Biologie et medecinE) en M2 with Medicine Faculty of Université de Lorraine
- T. Bastogne created and is now in charge research master << Biosanté Numérique >> with engineering school "Telecom Nancy"

- Master: S. Ferrigno, Experimental designs, 4.5h, M1, fourth year of EEIGM, Université de Lorraine, France
- Master: S. Ferrigno, Data analyzing and mining, 63h, M2, third year of Ecole des Mines, Université de Lorraine, France
- Master: S.Ferrigno, Modeling and forecasting, 43h, M1, second year of Ecole des Mines, Université de Lorraine, France
- Master: S.Ferrigno, Training projects, 18h, M1/M2, second and third year of Ecole des Mines, Université de Lorraine, France
- Master: A. Muller-Gueudin, Probability and Statistics, 160h, second year of ENSEM and ENSAIA, University of Lorraine, France.
- Master: A. Muller-Gueudin, Scientific calculation with Matlab, 20h, second year of ENSAIA, University of Lorraine, France.
- Master: R. Azaïs, Machine learning, 20h, M2, Université de Lorraine and third year of Telecom Nancy, France.
- Master: R. Azaïs, Machine learning, 20h, M1, second year of Ecole des Mines, Université de Lorraine, France.
- Master: J.-M. Monnez, Multivariate Analysis, Master 2 IFM (Ingénierie de la Finance de Marché), until June 2016.
- Master: A.Gégout-Petit, Statistics, modeling, 15h, future teacher, Université de Lorraine, France
- Master: A.Gégout-Petit, Statistics, modeling, data analysis, 80h, master in applied mathematics, Université de Lorraine, France
- Licence: S. Wantz-Mézières, Applied mathematics for management, financial mathematics, Probability and Statistics, 160h, I.U.T. (L1/L2/L3)
- Licence: S. Wantz-Mézières, Probability, 100h, first year in Telecom Nancy engineering school (initial and apprenticeship cursus)
- Master: J.-M. Monnez, Data Analysis, Statistical Learning, Master 2 IMOI (Ingénierie Mathématique et Outils Informatiques), until June 2016.
- Licence: A. Muller-Gueudin, Statistics, 60h, first year of ENSAIA, University of Lorraine, France.
- Licence: S. Ferrigno, Descriptive and inferential statistics, 60h, L2, second year of EEIGM, Université de Lorraine, France
- Licence: S. Ferrigno, Statistical modeling, 60h, L2, second year of EEIGM, Université de Lorraine, France
- Licence: S. Ferrigno, Mathematical and computational tools, 20h, L3, third year of EEIGM, Université de Lorraine, France
- Licence: S. Ferrigno, Training projects, 20h, L1/L3, first, second and third year of EEIGM, Université de Lorraine, France
- Licence: C. Lacaux: Probability and Statistic, 75h, L3, University of Avignon.
- Licence: C. Lacaux: Numerical simulation in probability, 36.75h, L3, University of Avignon.
- Licence: C. Lacaux: Probability and Statitics, 22.5h, L1, University of Avignon.
- Licence: C. Lacaux: Statistic techniques applied to SVT, 25.5h, L3, University of Avignon.
- Licence: C. Lacaux: Statistics, 24h, L2, University of Avignon.

10.2.2. Supervision

- PhD : Clémence Karmann, " Network inference for zero-inflated models", Grant : Inria-Cordis. Advisors: A. Gégout-Petit, A. Muller-Gueudin.

- PhD : Florine Gréciet, " Modèles markoviens déterministes par morceaux cachés pour la propagation de fissures", grant CIFRE SAFRAN AIRCRAFT ENGINES, Advisors : R. Azaïs, A. Gégout-Petit.
- PhD : Kévin Duarte, "Aide à la décision médicale et télémédecine dans le suivi de l'insuffisance cardiaque", Advisors : J.-M. Monnez and E. Albuisson.
- PhD : P. Retif. Modeling, digital simulation and analysis of nanoparticles-X ray interaction. Applications to augmented radiotherapy. Theses, Université de Lorraine, Mar. 2016.
- Post-doc: Florian Bouguet. Advisors: Romain Azaïs, Anne Gégout-Petit, Aurélie Muller-Gueudin.
- Post-doc: Benoît Henry (starting in Dec. 2016). Advisors: Romain Azaïs with Inria team Madynes.
- Master: Yaojie Shi, Toulouse School of economics, 2016. « Analyse de données transcriptomiques et protéomiques en oncologie », Advisors: A. Gégout-Petit, A. Muller-Gueudin, B. Bastien (Société Transgene, Strasbourg).
- Master: Yuyan Cao, Toulouse School of economics, 2016. " Spatio-temporal Bayesian models for the analysis of esca disease", with Inra Bordeaux. Advisor: A. Gégout-Petit, L. Guérin-Dubrana.
- Master: Félicie Bonte, Master Ecologie Ecologie Lille, AgroParistech Nancy et Museum National d'Histoire Naturelle 2016. « Etude des modifications de la croissance et du développement des plantes herbacées en forêt en réponse aux changements globaux », co-direction AgroParistech Nancy. Advisors: A. Gégout-Petit, Jean-Claude Gégout, Serge Muller.
- Master: all BIGS members regularly supervise project and internship of master IMOI students
- Engineering school: all BIGS members regularly supervise project of "Ecole des Mines ", ENSEM or EEIGM students

10.2.3. Juries

- HDR, Bruno Scherrer, "Contributions algorithmiques au contrôle optimal stochastique à temps discret et horizon infini", Université de Lorraine, July, 2016, Examinator, A. Gégout-Petit
- HDR, Corine Hahn, "Penser la question didactique pour la formation en alternance dans l'enseignement supérieur. Dispositifs frontières, Statistique et Management." Université Lyon 2, May, 2016, Examinator, A. Gégout-Petit
- PhD, Florian Bouguet, "Etude quantitative de processus de Markov déterministes par morceaux issus de la modélisation", Université de Rennes, June, 2016, Referee: A. Gégout-Petit
- PhD, Houda Ghamlouch, "Modélisation de la dégradation, maintenance conditionnelle et pronostic : usage des processus de diffusion", Université Technologique de Troyes, June, 2016, Referee: A. Gégout-Petit
- PhD, Etienne Baratchart, "Etude quantitative des aspects dynamiques et spatiaux du développement métastatique à l'aide de modèles mathématiques", Université de Bordeaux, February, 2016, Referee: A. Gégout-Petit
- PhD, Johann Cuenin, Sur les modèles Tweedie multivariés, Université de Besancon, December, Examinator: A. Gégout-Petit
- PhD : Clémence Chamard-Jovenin, Impact d'une surexpression d'ERα36 et/ou d'une exposition aux alkylphénols sur la physiopathologie de la glande mammaire, Université de Lorraine, 9 décembre 2016. Examinator : A. Muller-Gueudin.
- PhD : M. Ben Abdallah, Université de Lorraine, "Un modèle de l'évolution des gliomes diffus de bas grade sous chimiothérapie", December, 12, 2016, jury member: S. Wantz-Mézières.
- PhD : Marc Bourotte, Générateur stochastique de temps multisite basé sur un champ gaussien multivarié, INRA, Équipe BioSP, July, 4th,2016, President : C. Lacaux.
- PhD : Nhu Dang, Estimation des indices de stabilité et d'autosimilarité par variations de puissances négatives, Laboratoire Jean Kuntzmann Grenoble, July, 5th,2016, Examinator : C. Lacaux.

10.3. Popularization

- A. Gégout-Petit is involved in the promotion of study in the fields of mathematics in Lorraine university. She was very active in the realisation of the video for the promotion of Mathematical studies http://videos.univ-lorraine.fr/index.php?act=view&id=3236.
- A. Gégout-Petit participates to the "Table ronde Bourse aux technologues, Big data et industrie du futur", Ecole des Mines de Nancy, November, 2016.
- Animation d'ateliers MATh.en.JEANS en collège dans la région de Nancy (Romain Azaïs, Clémence Karmann)
- S. Ferrigno: Advisor of a group of students, "La main à la Pâte" project, elementary schools, Nancy, January-June 2016
- S. Ferrigno: Advisor of a group of students, "La main à la Pâte" project, Institut médico-éducatif (IME), Commercy, September-December 2016
- S. Ferrigno: Advisor of a group of students, "De Léonard de Vinci au Drone" project, Collège Paul Verlaine, Malzéville, December 2016-February 2017.

11. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] B. SCHERRER.*Contributions algorithmiques au contrôle optimal stochastique à temps discret et horizon infini*, Université de Lorraine (Nancy), June 2016, Habilitation à diriger des recherches, https://hal.inria.fr/tel-01400208.

Articles in International Peer-Reviewed Journal

[2] R. AZAÏS, A. MULLER-GUEUDIN.*Optimal choice among a class of nonparametric estimators of the jump rate for piecewise-deterministic Markov processes*, in "Electronic journal of statistics ", 2016, https://hal.archives-ouvertes.fr/hal-01168651.

[3] O. COLLIGNON, J.-M. MONNEZ.*Clustering of the values of a response variable and simultaneous covariate selection using a stepwise algorithm*, in "Applied Mathematics", 2016, vol. 07, p. 1639 - 1648 [*DOI :* 10.4236/AM.2016.715141], https://hal.inria.fr/hal-01395535.

[4] C. LACAUX, G. SAMORODNITSKY.*Time-changed Extremal Process as a Random Sup Measure*, in "Bernoulli journal", 2016, vol. 22, n^{o} 4, p. 1979–2000, https://hal.archives-ouvertes.fr/hal-01102343.

[5] S. LI, F. BONNEU, J. J. CHADOEUF, D. PICART, A. GÉGOUT-PETIT, L. GUERIN-DUBRANA.*Spatial and Temporal Pattern Analyses 1 of Esca Grapevine Disease in Vineyards in France*, in "Phytopathology", 2017, https://hal.inria.fr/hal-01205332.

[6] I.-C. MORARESCU, S. MARTIN, A. GIRARD, A. MULLER-GUEUDIN.*Coordination in networks of linear impulsive agents*, in "IEEE Transactions on Automatic Control", September 2016, vol. 61, n^{o} 9, p. 2402-2415 [*DOI :* 10.1109/TAC.2015.2492058], https://hal.archives-ouvertes.fr/hal-01096071.

[7] G. NICHIL, P. VALLOIS.*Provisioning against borrowers default risk*, in "Insurance: Mathematics and Economics", 2016, vol. 66, p. 29-43 [*DOI :* 10.1016/J.INSMATHECO.2015.10.004], https://hal.archives-ouvertes.fr/hal-01224520.

[8] P. RETIF, T. BASTOGNE, M. BARBERI-HEYOB.*Robustness analysis of a Geant4-Gate simulator for nano-radiosensitizers characterization*, in "IEEE Transactions on NanoBioscience", April 2016, vol. 15, n^{o} 3, p. 209-217 [*DOI :* 10.1109/TNB.2016.2527720], https://hal.archives-ouvertes.fr/hal-01326803.

[9] P. RETIF, A. REINHARD, H. PAQUOT, V. JOUAN-HUREAUX, A. CHATEAU, L. SANCEY, M. BARBERI-HEYOB, S. PINEL, T. BASTOGNE.*Monte Carlo simulations guided by imaging to predict the in vitro ranking of radiosensitizing nanoparticles*, in "International Journal of Nanomedicine", November 2016, vol. 11, p. 6169-6179 [*DOI :* 10.2147/IJN.S111320], https://hal.archives-ouvertes.fr/hal-01407060.

[10] B. SCHERRER.*Improved and Generalized Upper Bounds on the Complexity of Policy Iteration*, in "Mathematics of Operations Research", February 2016, Markov decision processes ; Dynamic Programming ; Analysis of Algorithms [*DOI :* 10.1287/MOOR.2015.0753], https://hal.inria.fr/hal-00829532.

[11] M. TOUSSAINT, S. PINEL, F. AUGER, N. DURIEUX, M. THOMASSIN, E. THOMAS, A. MOUSSARON, D. MENG, F. PLÉNAT, M. AMOUROUX, T. BASTOGNE, C. FROCHOT, O. TILLEMENT, F. LUX, M. BARBERI-HEYOB.*Proton MR spectroscopy and diffusion MR imaging monitoring to predict tumor response to interstitial photodynamic therapy for glioblastoma*, in "Theranostics", 2017, https://hal.archives-ouvertes.fr/hal-01399256.

[12] J.-B. TYLCZ, T. BASTOGNE, A. BOURGUIGNON, C. FROCHOT, M. BARBERI-HEYOB.*Realtime tracking of the photobleaching trajectory during photodynamic therapy*, in "IEEE Transactions on Biomedical Engineering", 2017, 8 [*DOI :* 10.1109/TBME.2016.2620239], https://hal.archives-ouvertes.fr/hal-01205739.

Invited Conferences

[13] M. BEN ABDALLAH, M. BLONSKI, S. WANTZ-MÉZIÈRES, Y. GAUDEAU, L. TAILLANDIER, J.-M. MOUREAUX.*Evaluation statistique de la segmentation manuelle de données IRM de gliomes diffus de bas grade*, in "18e Colloque Compression et Repre´sentation des Signaux Audiovisuels, CORESA 2016", Nancy, France, May 2016, https://hal.archives-ouvertes.fr/hal-01316788.

[14] M. BEN ABDALLAH, M. BLONSKI, S. WANTZ-MÉZIÈRES, Y. GAUDEAU, L. TAILLANDIER, J.-M. MOUREAUX.*Modèles prédictifs pour les gliomes diffus de bas grade sous chimiothérapie*, in "18e Colloque Compression et Repre´sentation des Signaux Audiovisuels, CORESA 2016", Nancy, France, May 2016, https://hal.archives-ouvertes.fr/hal-01316799.

[15] M. BEN ABDALLAH, M. BLONSKI, S. WANTZ-MÉZIÈRES, Y. GAUDEAU, L. TAILLANDIER, J.-M. MOUREAUX.*Modèles prédictifs pour les gliomes diffus de bas grade sous chimiothérapie*, in "Modélisation biostatistique et biomathématique des données d'imagerie en cancérologie", Bordeaux, France, Cancéropôle Grand Sud-Ouest, April 2016, Présentation Poster, https://hal.archives-ouvertes.fr/hal-01321281.

[16] M. BEN ABDALLAH, M. BLONSKI, S. WANTZ-MÉZIÈRES, Y. GAUDEAU, L. TAILLANDIER, J.-M. MOUREAUX.*Predictive models for diffuse low-grade glioma patients under chemotherapy*, in "38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBC'16", Orlando, Florida, United States, August 2016, https://hal.archives-ouvertes.fr/hal-01316865.

[17] M. BEN ABDALLAH, M. BLONSKI, S. WANTZ-MÉZIÈRES, Y. GAUDEAU, L. TAILLANDIER, J.-M. MOUREAUX.*Statistical evaluation of manual segmentation of a diffuse low-grade glioma MRI dataset*, in "38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBC'16", Orlando, Florida, United States, August 2016, https://hal.archives-ouvertes.fr/hal-01316879.

International Conferences with Proceedings

[18] M. ACHARD, S. ACHERAR, P. ALTHUSER, J.-C. ANDRE, A. PHILIPPE, M. BARBERI-HEYOB, F. BAROS, T. BASTOGNE, C. BONINSEGNA, C. BOURA, L. COLOMBEAU, C. FROCHOT, V. JOUAN-HUREAUX, S. GORIA, J. LANDON, A. MOHD GAZZALI, S. PINEL, T. ROQUES-CARMES, N. THOMAS, M. TOUSSAINT, R. VANDERESSE, Z. YOUSSEF.*PDTeam's project: targeting to improve PDT selectivity*, in "Photodynamic Therapy and Photodiagnosis update", Nancy, France, October 2016, p. Poster PC-028, Présentation Poster, https://hal.archives-ouvertes.fr/hal-01408912.

[19] K. DUARTE, J.-M. MONNEZ, E. ALBUISSON.*Valeur pronostique d'une estimation du volume plasmatique dans l'insuffisance cardiaque*, in "48èmes Journées de Statistique de la Société Française de Statistique", Montpellier, France, May 2016, https://hal.archives-ouvertes.fr/hal-01321101.

[20] A. GÉGOUT-PETIT, S. LI.*Two-step centered spatio-temporal auto-logistic regression model*, in "SADA416, Applied Statistics for Development in Africa", Cotonou, Benin, November 2016, https://hal.inria.fr/hal-01394868.

[21] J. PEROLAT, B. PIOT, B. SCHERRER, O. PIETQUIN.*On the Use of Non-Stationary Strategies for Solving Two-Player Zero-Sum Markov Games*, in "19th International Conference on Artificial Intelligence and Statistics (AISTATS 2016)", Cadiz, Spain, Proceedings of the International Conference on Artificial Intelligences and Statistics, May 2016, https://hal.inria.fr/hal-01291495.

[22] J. PÉROLAT, B. PIOT, M. GEIST, B. SCHERRER, O. PIETQUIN.*Softened Approximate Policy Iteration for Markov Games*, in "ICML 2016 - 33rd International Conference on Machine Learning", New York City, United States, June 2016, https://hal.inria.fr/hal-01393328.

Conferences without Proceedings

[23] L. BATISTA, T. BASTOGNE, E.-H. DJERMOUNE.*Identification of dynamical biological systems based on mixed-effect models*, in "31st ACM Symposium on Applied Computing", Pisa, Italy, April 2016, https://hal.archives-ouvertes.fr/hal-01205738.

[24] L. BATISTA, T. BASTOGNE, E.-H. DJERMOUNE.*Mixed-effects ARX model identification of dynamical systems*, in "25th Meeting of the Population Approach Group in Europe, PAGE 2016", Lisboa, Portugal, June 2016, PAGE 25 (2016) Abstr 5807, Présentation Poster, https://hal.archives-ouvertes.fr/hal-01320594.

[25] P. HÉNA, A. REINHARD, P. RETIF, A. CHATEAU, V. JOUAN-HUREAUX, L. SANCEY, T. BASTOGNE, P. QUETIN, S. PINEL, M. BARBERI-HEYOB.*Screening process of radiosensitizing nanoparticles based on basic in vitro experimental data and in silico analysis*, in "13e Colloque Nano-hybrides", Porquerolles, France, ILM, Lyon 1, May 2016, Présentation Poster, https://hal.archives-ouvertes.fr/hal-01312945.

Scientific Books (or Scientific Book chapters)

[26] M. SCHLIEMANN-BULLINGER, D. FEY, T. BASTOGNE, R. FINDEISEN, P. SCHEURICH, E. BULLINGER.*The experimental side of parameter estimation*, in "Uncertainty in Biology - A Computational Modeling Approach", L. GERIS, D. GOMEZ-CABRERO (editors), Studies in Mechanobiology, Tissue Engineering and Biomaterials, Springer, 2016, vol. 17, p. 127-154, https://hal.archives-ouvertes.fr/hal-01256462.

Other Publications

[27] R. AZAÏS, B. DELYON, F. PORTIER.*Integral estimation based on Markovian design*, September 2016, 45 pages, https://hal.archives-ouvertes.fr/hal-01360647.

[28] R. AZAÏS, J.-B. DURAND, C. GODIN.*Approximation of trees by self-nested trees*, September 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01294013.

[29] R. AZAÏS, A. GENADOT.*A new characterization of the jump rate for piecewise-deterministic Markov processes with discrete transitions*, June 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01334847.

[30] R. AZAÏS, A. GENADOT, B. HENRY.*Inference for conditioned Galton-Watson trees from their Harris path*, September 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01360650.

[31] M. BENAÏM, F. BOUGUET, B. CLOEZ.*Ergodicity of inhomogeneous Markov chains through asymptotic pseudotrajectories*, November 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01401981.

[32] F. BOUGUET.*A Probabilistic Look at Growth-Fragmentation Equations*, September 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01362555.

[33] F. GRECIET, R. AZAÏS, A. GEGOUT-PETIT, M. BIRET.*Modèle markovien déterministe par morceaux caché pour la propagation de fissure*, October 2016, Mathématiques, oxygène du numérique, Poster, https://hal.archives-ouvertes.fr/hal-01398288.

[34] P. HÉNA, A. REINHARD, P. RETIF, A. CHATEAU, V. JOUAN-HUREAUX, L. SANCEY, T. BASTOGNE, M. BARBERI-HEYOB, S. PINEL.*Pouvoir radiopotentialisant in vitro de nanoparticules hybrides à base de métaux*, November 2016, p. 59- poster 14, 10ème Forum du Cancéropôle Grand-Est, Poster, https://hal.archives-ouvertes.fr/hal-01409010.

[35] A. LAGNOUX, S. MERCIER, P. VALLOIS.*Statistical significance for sequence analysis. Illustration of new results on length and position of the local score*, April 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01301246.

References in notes

[36] O. ARINO, M. KIMMEL, G. F. WEBB.*Mathematical modeling of the loss of telomere sequences*, in "Journal of theoretical biology", 1995, vol. 177, n^{o} 1, p. 45–57.

[37] R. AZAÏS.*A recursive nonparametric estimator for the transition kernel of a piecewise-deterministic Markov process*, in "ESAIM: Probability and Statistics", 2014, vol. 18, p. 726–749.

[38] R. AZAÏS, F. DUFOUR, A. GÉGOUT-PETIT.*Nonparametric estimation of the jump rate for non-homogeneous marked renewal processes*, in "Annales de l'Institut Henri Poincaré, Probabilités et Statistiques", Institut Henri Poincaré, 2013, vol. 49, n^{o} 4, p. 1204–1231.

[39] R. AZAÏS, F. DUFOUR, A. GÉGOUT-PETIT.*Nonparametric estimation of the jump rate for piecewise-deterministic Markov processes*, in "Scandinavian Journal of Statistics", 2014, 26.

[40] J. M. BARDET, G. LANG, G. OPPENHEIM, A. PHILIPPE, S. STOEV, M. TAQQU.*Semi-parametric estimation of the long-range dependence parameter: a survey*, in "Theory and applications of long-range dependence", Birkhauser Boston, 2003, p. 557-577.

[41] T. BASTOGNE, S. MÉZIÈRES-WANTZ, N. RAMDANI, P. VALLOIS, M. BARBERI-HEYOB.*Identification of pharmacokinetics models in the presence of timing noise*, in "Eur. J. Control", 2008, vol. 14, n° 2, p. 149–157, http://dx.doi.org/10.3166/ejc.14.149-157.

[42] T. BASTOGNE, A. SAMSON, P. VALLOIS, S. WANTZ-MEZIERES, S. PINEL, D. BECHET, M. BARBERI-HEYOB.*Phenomenological modeling of tumor diameter growth based on a mixed effects model*, in "Journal of theoretical biology", 2010, vol. 262, n° 3, p. 544–552.

[43] L. BATISTA, T. BASTOGNE, E.-H. DJERMOUNE.*Identification of dynamical biological systems based on random effects models*, in "37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBC 2015", Milan, Italy, August 2015, https://hal.archives-ouvertes.fr/hal-01159193.

[44] A. BENASSI, S. JAFFARD, D. ROUX.*Elliptic Gaussian random processes*, in "Rev. Mat. Iberoamericana", 1997, vol. 13, n° 1, p. 19–90.

[45] D. BERTSEKAS, J. TSITSIKLIS.*Neurodynamic Programming*, Athena Scientific, 1996.

[46] H. BIERMÉ, C. LACAUX.*Hölder regularity for operator scaling stable random fields*, in "Stochastic Process. Appl.", 2009, vol. 119, n° 7, p. 2222–2248, http://dx.doi.org/10.1016/j.spa.2008.10.008.

[47] H. BIERMÉ, C. LACAUX, H.-P. SCHEFFLER.*Multi-operator Scaling Random Fields*, in "Stochastic Processes and their Applications", 2011, vol. 121, n° 11, p. 2642-2677, MAP5 2011-01 [*DOI :* 10.1016/J.SPA.2011.07.002], http://hal.archives-ouvertes.fr/hal-00551707/en/.

[48] H. BIERMÉ, C. LACAUX, Y. XIAO.*Hitting probabilities and the Hausdorff dimension of the inverse images of anisotropic Gaussian random fields*, in "Bull. Lond. Math. Soc.", 2009, vol. 41, n° 2, p. 253–273, http://dx.doi.org/10.1112/blms/bdn122.

[49] T. BOURGERON, Z. XU, M. DOUMIC, M. T. TEIXEIRA.*The asymmetry of telomere replication contributes to replicative senescence heterogeneity*, in "Scientific reports", 2015, vol. 5.

[50] A. CHRONOPOULOU, S. TINDEL.*On inference for fractional differential equations*, in "Statistical Inference for Stochastic Processes", 2013, vol. 16, n° 1, p. 29–61.

[51] J. F. COEURJOLLY.*Simulation and identification of the fractional brownian motion: a bibliographical and comparative study*, in "Journal of Statistical Software", 2000, vol. 5, p. 1–53.

[52] S. COHEN, C. LACAUX, M. LEDOUX.*A general framework for simulation of fractional fields*, in "Stochastic Process. Appl.", 2008, vol. 118, n° 9, p. 1489–1517, http://dx.doi.org/10.1016/j.spa.2007.09.008.

[53] M. H. DAVIS.*Piecewise-deterministic Markov processes: A general class of non-diffusion stochastic models*, in "Journal of the Royal Statistical Society. Series B (Methodological)", 1984, p. 353–388.

[54] A. DEYA, S. TINDEL.*Rough Volterra equations. I. The algebraic integration setting*, in "Stoch. Dyn.", 2009, vol. 9, n^{o} 3, p. 437–477, http://dx.doi.org/10.1142/S0219493709002737.

[55] J. A. DOORNIK, H. HANSEN.*An omnibus test for univariate and multivariate normality**, in "Oxford Bulletin of Economics and Statistics", 2008, vol. 70, n^{o} s1, p. 927–939.

[56] M. DOUMIC, M. HOFFMANN, N. KRELL, L. ROBERT.*Statistical estimation of a growth-fragmentation model observed on a genealogical tree*, in "Bernoulli", 2015, vol. 21, n^{o} 3, p. 1760–1799.

[57] J. FEARNLEY.*Exponential lower bounds for policy iteration*, in "37th international colloquium conference on Automata, languages and programming: Part II", Berlin, Heidelberg, ICALP'10, Springer-Verlag, 2010, p. 551–562.

[58] S. FERRIGNO, G. R. DUCHARME.*Un test d'adéquation global pour la fonction de répartition conditionnelle*, in "Comptes Rendus Mathematique", 2005, vol. 341, n^{o} 5, p. 313–316.

[59] S. FERRIGNO, M. MAUMY-BERTRAND, A. MULLER.*Uniform law of the logarithm for the local linear estimator of the conditional distribution function*, in "C. R. Math. Acad. Sci. Paris", 2010, vol. 348, n^{o} 17-18, p. 1015–1019, http://dx.doi.org/10.1016/j.crma.2010.08.003.

[60] J. FRIEDMAN, T. HASTIE, R. TIBSHIRANI.*Sparse inverse covariance estimation with the graphical lasso*, in "Biostatistics", 2008, vol. 9, n^{o} 3, p. 432–441.

[61] A. GENADOT, M. THIEULLEN.*Averaging for a fully coupled piecewise-deterministic markov process in infinite dimensions*, in "Advances in Applied Probability", 2012, vol. 44, n^{o} 3, p. 749–773.

[62] C. GIRAUD, S. HUET, N. VERZELEN.*Graph selection with GGMselect*, in "Statistical applications in genetics and molecular biology", 2012, vol. 11, n^{o} 3.

[63] M. GRABISCH, T. MUROFUSHI, M. SUGENO.*Fuzzy measure of fuzzy events defined by fuzzy integrals*, in "Fuzzy Sets and Systems", 1992, vol. 50, n^{o} 3, p. 293–313.

[64] M. GUBINELLI, S. TINDEL.*Rough evolution equations*, in "Ann. Probab.", 2010, vol. 38, n^{o} 1, p. 1–75, http://dx.doi.org/10.1214/08-AOP437.

[65] S. J. HABERMAN.*Algorithm AS 51: Log-linear fit for contingency tables*, in "Applied Statistics", 1972, p. 218–225.

[66] T. HANSEN, U. ZWICK.*Lower Bounds for Howard's Algorithm for Finding Minimum Mean-Cost Cycles*, in "ISAAC (1)", 2010, p. 415-426.

[67] S. HERRMANN, P. VALLOIS.*From persistent random walk to the telegraph noise*, in "Stoch. Dyn.", 2010, vol. 10, n^{o} 2, p. 161–196, http://dx.doi.org/10.1142/S0219493710002905.

[68] J. HU, W.-C. WU, S. SASTRY.*Modeling subtilin production in bacillus subtilis using stochastic hybrid systems*, in "Hybrid Systems: Computation and Control", Springer, 2004, p. 417–431.

[69] R. KEINJ, T. BASTOGNE, P. VALLOIS.*Multinomial model-based formulations of TCP and NTCP for radiotherapy treatment planning*, in "Journal of Theoretical Biology", June 2011, vol. 279, n^{o} 1, p. 55-62 [*DOI :* 10.1016/J.JTBI.2011.03.025], http://hal.inria.fr/hal-00588935/en.

[70] R. KOENKER.*Quantile regression*, Cambridge university press, 2005, n^{o} 38.

[71] H. J. KUSHNER, G. YIN.*Stochastic approximation and recursive algorithms and applications*, Springer Science & Business Media, 2003, vol. 35.

[72] Y. A. KUTOYANTS.*Statistical inference for ergodic diffusion processes*, Springer Series in Statistics, Springer-Verlag London Ltd., London, 2004, xiv+481.

[73] C. LACAUX.*Real Harmonizable Multifractional Lévy Motions*, in "Ann. Inst. Poincaré.", 2004, vol. 40, n^{o} 3, p. 259–277.

[74] C. LACAUX.*Series representation and simulation of multifractional Lévy motions*, in "Adv. in Appl. Probab.", 2004, vol. 36, n^{o} 1, p. 171–197, http://dx.doi.org/10.1239/aap/1077134469.

[75] C. LACAUX, J.-M. LOUBES.*Hurst exponent estimation of fractional Lévy motion*, in "ALEA Lat. Am. J. Probab. Math. Stat.", 2007, vol. 3, p. 143–164.

[76] C. LACAUX, R. MARTY.*From invariance principles to a class of multifractional fields related to fractional sheets*, 2011, MAP5 2011-08, http://hal.archives-ouvertes.fr/hal-00592188/en/.

[77] M. LAVIELLE.*Mixed effects models for the population approach: models, tasks, methods and tools*, CRC Press, 2014.

[78] L. LEBART.*On the Benzecri's method for computing eigenvectors by stochastic approximation (the case of binary data)*, in "Compstat 1974 (Proc. Sympos. Computational Statist., Univ. Vienna, Vienna, 1974)", Vienna, Physica Verlag, 1974, p. 202–211.

[79] B. LESNER, B. SCHERRER.*Non-Stationary Approximate Modified Policy Iteration*, in "ICML 2015", Lille, France, July 2015, https://hal.inria.fr/hal-01186664.

[80] T. LYONS, Z. QIAN.*System control and rough paths*, Oxford mathematical monographs, Clarendon Press, 2002, http://books.google.com/books?id=H9fRQNIngZYC.

[81] J.-L. MARICHAL.*An axiomatic approach of the discrete Choquet integral as a tool to aggregate interacting criteria*, in "Fuzzy Systems, IEEE Transactions on", 2000, vol. 8, n^{o} 6, p. 800–807.

[82] N. MEINSHAUSEN, P. BÜHLMANN.*High-dimensional graphs and variable selection with the lasso*, in "The Annals of Statistics", 2006, p. 1436–1462.

[83] J.-M. MONNEZ.*Approximation stochastique en analyse factorielle multiple*, in "Ann. I.S.U.P.", 2006, vol. 50, n^{o} 3, p. 27–45.

[84] J.-M. MONNEZ.*Stochastic approximation of the factors of a generalized canonical correlation analysis*, in "Statist. Probab. Lett.", 2008, vol. 78, n^{o} 14, p. 2210–2216, http://dx.doi.org/10.1016/j.spl.2008.01.088.

[85] J.-M. MONNEZ.*Convergence d'un processus d'approximation stochastique en analyse factorielle*, in "Publ. Inst. Statist. Univ. Paris", 1994, vol. 38, n^{o} 1, p. 37–55.

[86] E. NADARAYA.*On non-parametric estimates of density functions and regression curves*, in "Theory of Probability & Its Applications", 1965, vol. 10, n^{o} 1, p. 186–190.

[87] A. NEUENKIRCH, I. NOURDIN, A. RÖSSLER, S. TINDEL.*Trees and asymptotic expansions for fractional stochastic differential equations*, in "Ann. Inst. Henri Poincaré Probab. Stat.", 2009, vol. 45, n^{o} 1, p. 157–174, http://dx.doi.org/10.1214/07-AIHP159.

[88] A. NEUENKIRCH, S. TINDEL.*A least square-type procedure for parameter estimation in stochastic differential equations with additive fractional noise*, in "Statistical Inference for Stochastic Processes", 2014, vol. 17, n^{o} 1, p. 99–120.

[89] I. POST, Y. YE.*The simplex method is strongly polynomial for deterministic Markov decision processes*, arXiv:1208.5083v2, 2012.

[90] M. PUTERMAN.*Markov Decision Processes*, Wiley, New York, 1994.

[91] Q. QI, J. A. WATTIS, H. M. BYRNE.*Stochastic simulations of normal aging and Werner's syndrome*, in "Bulletin of mathematical biology", 2014, vol. 76, n^{o} 6, p. 1241–1269.

[92] P. RETIF.*Modeling, digital simulation and analysis of nanoparticles-X ray interaction. Applications to augmented radiotherapy.*, Université de Lorraine, March 2016, https://hal.archives-ouvertes.fr/tel-01376033.

[93] B. ROYNETTE, P. VALLOIS, M. YOR.*Brownian penalisations related to excursion lengths, VII*, in "Annales de l'IHP Probabilités et statistiques", 2009, vol. 45, n^{o} 2, p. 421–452.

[94] F. RUSSO, P. VALLOIS.*Stochastic calculus with respect to continuous finite quadratic variation processes*, in "Stochastics: An International Journal of Probability and Stochastic Processes", 2000, vol. 70, n^{o} 1-2, p. 1–40.

[95] F. RUSSO, P. VALLOIS.*Elements of stochastic calculus via regularization*, in "Séminaire de Probabilités XL", Berlin, Lecture Notes in Math., Springer, 2007, vol. 1899, p. 147–185, http://dx.doi.org/10.1007/978-3-540-71189-6_7.

[96] P. SALMINEN, P. VALLOIS.*On maximum increase and decrease of Brownian motion*, in "Annales de l'Institut Henri Poincare (B) Probability and Statistics", Elsevier, 2007, vol. 43, n^{o} 6, p. 655–676.

[97] B. SCHERRER, M. GHAVAMZADEH, V. GABILLON, B. LESNER, M. GEIST.*Approximate Modified Policy Iteration and its Application to the Game of Tetris*, in "Journal of Machine Learning Research", 2015, vol. 16, p. 1629–1676, A paraître, https://hal.inria.fr/hal-01091341.

[98] B. SCHERRER, B. LESNER.*On the Use of Non-Stationary Policies for Stationary Infinite-Horizon Markov Decision Processes*, in "NIPS 2012 - Neural Information Processing Systems", South Lake Tahoe, United States, December 2012, https://hal.inria.fr/hal-00758809.

[99] B. SCHERRER.*Performance Bounds for Lambda Policy Iteration and Application to the Game of Tetris*, in "Journal of Machine Learning Research", January 2013, vol. 14, p. 1175-1221, https://hal.inria.fr/hal-00759102.

[100] B. SCHERRER.*Approximate Policy Iteration Schemes: A Comparison*, in "ICML - 31st International Conference on Machine Learning - 2014", Pékin, China, June 2014, https://hal.inria.fr/hal-00989982.

[101] B. SCHERRER.*Improved and Generalized Upper Bounds on the Complexity of Policy Iteration*, in "Mathematics of Operations Research", 2015, A paraître.

[102] L. SHAPLEY.*Stochastic Games*, in "Proceedings of the National Academy of Sciences", 1953, vol. 39, n^o 10, p. 1095-1100.

[103] C. A. TUDOR, F. G. VIENS.*Statistical aspects of the fractional stochastic calculus*, in "Ann. Statist.", 2007, vol. 35, n^o 3, p. 1183–1212, http://dx.doi.org/10.1214/009053606000001541.

[104] P. VALLOIS, C. S. TAPIERO.*Memory-based persistence in a counting random walk process*, in "Phys. A.", 2007, vol. 386, n^o 1, p. 303–307, http://dx.doi.org/10.1016/j.physa.2007.08.027.

[105] P. VALLOIS.*The range of a simple random walk on Z*, in "Advances in applied probability", 1996, p. 1014–1033.

[106] N. VILLA-VIALANEIX.*An introduction to network inference and mining*, 2015, http://wikistat.fr/, (consulté le 22/07/2015), http://www.nathalievilla.org/doc/pdf//wikistat-network_compiled.pdf.

[107] Z. XU, K. D. DUC, D. HOLCMAN, M. T. TEIXEIRA.*The length of the shortest telomere as the major determinant of the onset of replicative senescence*, in "Genetics", 2013, vol. 194, n^o 4, p. 847–857.

[108] Y. YE.*The Simplex and Policy-Iteration Methods Are Strongly Polynomial for the Markov Decision Problem with a Fixed Discount Rate*, in "Math. Oper. Res.", 2011, vol. 36, n^o 4, p. 593-603.

Team CAMUS

Compilation pour les Architectures MUlti-cœurS

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
Nancy - Grand Est

THEME
Architecture, Languages and Compilation

Table of contents

Team CAMUS

Creation of the Team: 2009 July 01

Keywords:

Computer Science and Digital Science:

1.1.1. - Multicore
1.1.4. - High performance computing
2.1.1. - Semantics of programming languages
2.1.6. - Concurrent programming
2.2.1. - Static analysis
2.2.3. - Run-time systems
2.2.4. - Parallel architectures
2.2.5. - GPGPU, FPGA, etc.
2.2.6. - Adaptive compilation

Other Research Topics and Application Domains:

4.5.1. - Green computing
6.1.1. - Software engineering
6.6. - Embedded systems

1. Members

Research Scientists

Arthur Charguéraud [Inria, Researcher, since Oct 2016]
Jens Gustedt [Inria, Senior Researcher, HDR]

Faculty Members

Philippe Clauss [Team leader, Univ. Strasbourg, Professor, HDR]
Cédric Bastoul [Univ. Strasbourg, Professor, HDR]
Alain Ketterlin [Univ. Strasbourg, Assistant Professor]
Vincent Loechner [Univ. Strasbourg, Assistant Professor]
Nicolas Magaud [Univ. Strasbourg, Assistant Professor]
Julien Narboux [Univ. Strasbourg, Assistant Professor]
Éric Violard [Univ. Strasbourg, Assistant Professor, HDR]

Technical Staff

Artiom Baloian [Inria, until Oct 2016]

PhD Students

Yann Barsamian [Univ. Strasbourg]
Luis Esteban Campostrini [Inria, until Jun 2016]
Paul Godard [Caldera, from Sep 2016]
Juan Manuel Martinez Caamaño [Univ. Strasbourg, until Oct 2016]
Harenome Ranaivoarivony-Razanajato [Univ. Strasbourg, from Oct 2016]
Mariem Saied [Inria & Univ. Strasbourg]
Daniel Salas [INSERM]
Maxime Schmitt [Univ. Strasbourg, from Sep 2016]

Post-Doctoral Fellows

Julien Pagès [Univ. Strasbourg, from Oct 2016]

Manuel Selva [Inria, from Sep 2016]

Administrative Assistant

Véronique Constant [Inria]

2. Overall Objectives

2.1. Overall Objectives

The CAMUS team is focusing on developing, adapting and extending automatic parallelizing and optimizing techniques, as well as proof and certification methods, for the efficient use of current and future multicore processors.

The team's research activities are organized into five main issues that are closely related to reach the following objectives: performance, correction and productivity. These issues are: static parallelization and optimization of programs (where all statically detected parallelisms are expressed as well as all "hypothetical" parallelisms which would be eventually taken advantage of at runtime), profiling and execution behavior modeling (where expressive representation models of the program execution behavior will be used as engines for dynamic parallelizing processes), dynamic parallelization and optimization of programs (such transformation processes running inside a virtual machine), and finally program transformations proof (where the correction of many static and dynamic program transformations has to be ensured).

3. Research Program

3.1. Research Directions

The various objectives we are expecting to reach are directly related to the search of adequacy between the sofware and the new multicore processors evolution. They also correspond to the main research directions suggested by Hall, Padua and Pingali in [24]. Performance, correction and productivity must be the users' perceived effects. They will be the consequences of research works dealing with the following issues:

- Issue 1: Static Parallelization and Optimization
- Issue 2: Profiling and Execution Behavior Modeling
- Issue 3: Dynamic Program Parallelization and Optimization, Virtual Machine
- Issue 4: Proof of Program Transformations for Multicores

Efficient and correct applications development for multicore processors needs stepping in every application development phase, from the initial conception to the final run.

Upstream, all potential parallelism of the application has to be exhibited. Here static analysis and transformation approaches (issue 1) must be processed, resulting in a *multi-parallel* intermediate code advising the running virtual machine about all the parallelism that can be taken advantage of. However the compiler does not have much knowledge about the execution environment. It obviously knows the instruction set, it can be aware of the number of available cores, but it does not know the effective available resources at any time during the execution (memory, number of free cores, etc.).

That is the reason why a "virtual machine" mechanism will have to adapt the application to the resources (issue 3). Moreover the compiler will be able to take advantage only of a part of the parallelism induced by the application. Indeed some program information (variables values, accessed memory adresses, etc.) being available only at runtime, another part of the available parallelism will have to be generated on-the-fly during the execution, here also, thanks to a dynamic mechanism.

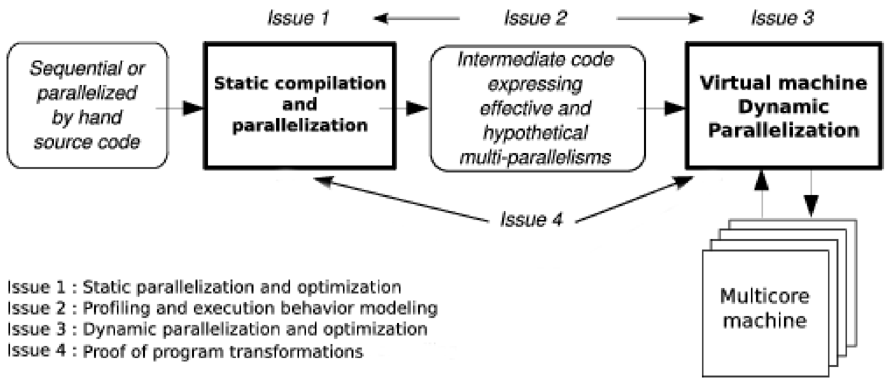

Figure 1. Automatic parallelizing steps for multicore architectures

This on-the-fly parallelism extraction will be performed using speculative behavior models (issue 2), such models allowing to generate speculative parallel code (issue 3). Between our behavior modeling objectives, we can add the behavior monitoring, or profiling, of a program version. Indeed current and future architectures complexity avoids assuming an optimal behavior regarding a given program version. A monitoring process will allow to select on-the-fly the best parallelization.

These different parallelizing steps are schematized on figure 1.

Our project lies on the conception of a production chain for efficient execution of an application on a multicore architecture. Each link of this chain has to be formally verified in order to ensure correction as well as efficiency. More precisely, it has to be ensured that the compiler produces a correct intermediate code, and that the virtual machine actually performs the parallel execution semantically equivalent to the source code: every transformation applied to the application, either statically by the compiler or dynamically by the virtual machine, must preserve the initial semantics. They must be proved formally (issue 4).

In the following, those different issues are detailed while forming our global and long term vision of what has to be done.

3.2. Static Parallelization and Optimization

Participants: Vincent Loechner, Philippe Clauss, Éric Violard, Cédric Bastoul, Arthur Charguéraud.

Static optimizations, from source code at compile time, benefit from two decades of research in automatic parallelization: many works address the parallelization of loop nests accessing multi-dimensional arrays, and these works are now mature enough to generate efficient parallel code [23]. Low-level optimizations, in the assembly code generated by the compiler, have also been extensively dealt for single-core and require few adaptations to support multicore architectures. Concerning multicore specific parallelization, we propose to explore two research directions to take full advantage of these architectures: adapting parallelization to multicore architecture and expressing many potential parallelisms.

3.3. Profiling and Execution Behavior Modeling

Participants: Alain Ketterlin, Philippe Clauss, Manuel Selva.

The increasing complexity of programs and hardware architectures makes it ever harder to characterize beforehand a given program's run time behavior. The sophistication of current compilers and the variety of transformations they are able to apply cannot hide their intrinsic limitations. As new abstractions like transactional memories appear, the dynamic behavior of a program strongly conditions its observed performance. All these reasons explain why empirical studies of sequential and parallel program executions have been considered increasingly relevant. Such studies aim at characterizing various facets of one or several program runs, *e.g.*, memory behavior, execution phases, etc. In some cases, such studies characterize more the compiler than the program itself. These works are of tremendous importance to highlight all aspects that escape static analysis, even though their results may have a narrow scope, due to the possible incompleteness of their input data sets.

3.4. Dynamic Parallelization and Optimization, Virtual Machine

Participants: Manuel Selva, Juan Manuel Martinez Caamaño, Luis Esteban Campostrini, Artiom Baloian, Mariem Saied, Daniel Salas, Philippe Clauss, Jens Gustedt, Vincent Loechner, Alain Ketterlin.

This link in the programming chain has become essential with the advent of the new multicore architectures. Still being considered as secondary with mono-core architectures, dynamic analysis and optimization are now one of the keys for controling those new mechanisms complexity. From now on, performed instructions are not only dedicated to the application functionalities, but also to its control and its transformation, and so in its own interest. Behaving like a computer virus, such a process should rather be qualified as a "vitamin". It perfectly knows the current characteristics of the execution environment and owns some qualitative information thanks to a behavior modeling process (issue 2). It appends a significant part of optimizing ability compared to a static compiler, while observing live resources availability evolution.

3.5. Proof of Program Transformations for Multicores

Participants: Éric Violard, Alain Ketterlin, Julien Narboux, Nicolas Magaud, Arthur Charguéraud.

Our main objective consists in certifying the critical modules of our optimization tools (the compiler and the virtual machine). First we will prove the main loop transformation algorithms which constitute the core of our system.

The optimization process can be separated into two stages: the transformations consisting in optimizing the sequential code and in exhibiting parallelism, and those consisting in optimizing the parallel code itself. The first category of optimizations can be proved within a sequential semantics. For the other optimizations, we need to work within a concurrent semantics. We expect the first stage of optimizations to produce data-race free code. For the second stage of optimizations, we will first assume that the input code is data-race free. We will prove those transformations using Appel's concurrent separation logic [25]. Proving transformations involving program which are not data-race free will constitute a longer term research goal.

4. Application Domains

4.1. Application Domains

Performance being our main objective, our developments' target applications are characterized by intensive computation phases. Such applications are numerous in the domains of scientific computations, optimization, data mining and multimedia.

Applications involving intensive computations are necessarily high energy consumers. However this consumption can be significantly reduced thanks to optimization and parallelization. Although this issue is not our prior objective, we can expect some positive effects for the following reasons:

- Program parallelization tries to distribute the workload equally among the cores. Thus an equivalent performance, or even a better performance, to a sequential higher frequency execution on one single core, can be obtained.
- Memory and memory accesses are high energy consumers. Lowering the memory consumption, lowering the number of memory accesses and maximizing the number of accesses in the low levels of the memory hierarchy (registers, cache memories) have a positive consequence on execution speed, but also on energy consumption.

5. Highlights of the Year

5.1. Highlights of the Year

Arthur Charguéraud, Inria Research Scientist, has joined the team in October 2016.

The first release of the speculative polyhedral loop parallelizer *Apollo*[0] has been published under the BSD 3-Clause Open Source License.

5.1.1. Awards

BEST PAPERS AWARDS :
[13] **Euro-Par 2016**. J. M. MARTINEZ CAAMAÑO, W. WOLFF, P. CLAUSS.

6. New Software and Platforms

6.1. Apollo

Automatic speculative POLyhedral Loop Optimizer
KEYWORD: Automatic parallelization
FUNCTIONAL DESCRIPTION

Apollo is dedicated to automatic, dynamic and speculative parallelization of loop nests that cannot be handled efficiently at compile-time. It is composed of a static part consisting of specific passes in the LLVM compiler suite, plus a modified Clang frontend, and a dynamic part consisting of a runtime system. It can apply on-the-fly any kind of polyhedral transformations, including tiling, and can handle nonlinear loops, as while-loops referencing memory through pointers and indirections.

- Participants: Manuel Selva, Juan Manuel Martinez Caamaño, Artiom Baloian, and Philippe Clauss
- Contact: Philippe Clauss
- URL: http://apollo.gforge.inria.fr

6.2. CLooG

Code Generator in the Polyhedral Model
FUNCTIONAL DESCRIPTION

CLooG is a free software and library to generate code (or an abstract syntax tree of a code) for scanning Z-polyhedra. That is, it finds a code (*e.g.* in C, FORTRAN...) that reaches each integral point of one or more parameterized polyhedra. CLooG has been originally written to solve the code generation problem for optimizing compilers based on the polyhedral model. Nevertheless it is used now in various area *e.g.* to build control automata for high-level synthesis or to find the best polynomial approximation of a function. CLooG may help in any situation where scanning polyhedra matters. While the user has full control on generated code quality, CLooG is designed to avoid control overhead and to produce a very effective code. CLooG is widely used (including by GCC and LLVM compilers), disseminated (it is installed by default by the main Linux distributions) and considered as the state of the art in polyhedral code generation.

- Participant: Cédric Bastoul
- Contact: Cédric Bastoul
- URL: http://www.cloog.org

6.3. Clan

A Polyhedral Representation Extraction Tool for C-Based High Level Languages

[0] http://apollo.gforge.inria.fr

FUNCTIONAL DESCRIPTION

Clan is a free software and library which translates some particular parts of high level programs written in C, C++, C# or Java into a polyhedral representation called OpenScop. This representation may be manipulated by other tools to, *e.g.*, achieve complex analyses or program restructurations (for optimization, parallelization or any other kind of manipulation). It has been created to avoid tedious and error-prone input file writing for polyhedral tools (such as CLooG, LeTSeE, Candl etc.). Using Clan, the user has to deal with source codes based on C grammar only (as C, C++, C# or Java). Clan is notably the frontend of the two major high-level compilers Pluto and PoCC.

- Participants: Cédric Bastoul
- Contact: Cédric Bastoul
- URL: http://icps.u-strasbg.fr/people/bastoul/public_html/development/clan/

6.4. Clay

Chunky Loop Alteration wizardrY
FUNCTIONAL DESCRIPTION

Clay is a free software and library devoted to semi-automatic optimization using the polyhedral model. It can input a high-level program or its polyhedral representation and transform it according to a transformation script. Classic loop transformations primitives are provided. Clay is able to check for the legality of the complete sequence of transformation and to suggest corrections to the user if the original semantics is not preserved.

- Participant: Cédric Bastoul
- Contact: Cédric Bastoul
- URL: http://icps.u-strasbg.fr/people/bastoul/public_html/development/clay/

6.5. IBB

Iterate-But-Better
FUNCTIONAL DESCRIPTION

IBB is a source-to-source xfor compiler which automatically translates any C source code containing xfor-loops into an equivalent source code where xfor-loops have been transformed into equivalent for-loops.

- Participants: Philippe Clauss and Cédric Bastoul
- Contact: Philippe Clauss
- URL: http://xfor.gforge.inria.fr

6.6. OpenScop

A Specification and a Library for Data Exchange in Polyhedral Compilation Tools
FUNCTIONAL DESCRIPTION

OpenScop is an open specification that defines a file format and a set of data structures to represent a static control part (SCoP for short), i.e., a program part that can be represented in the polyhedral model. The goal of OpenScop is to provide a common interface to the different polyhedral compilation tools in order to simplify their interaction. To help the tool developers to adopt this specification, OpenScop comes with an example library (under 3-clause BSD license) that provides an implementation of the most important functionalities necessary to work with OpenScop.

- Participant: Cédric Bastoul
- Contact: Cédric Bastoul
- URL: http://icps.u-strasbg.fr/people/bastoul/public_html/development/openscop/

6.7. PolyLib

The Polyhedral Library
FUNCTIONAL DESCRIPTION

PolyLib is a C library of polyhedral functions, that can manipulate unions of rational polyhedra of any dimension. It was the first to provide an implementation of the computation of parametric vertices of a parametric polyhedron, and the computation of an Ehrhart polynomial (expressing the number of integer points contained in a parametric polytope) based on an interpolation method. Vincent Loechner is the maintainer of this software.

- Participant: Vincent Loechner
- Contact: Vincent Loechner
- URL: http://icps.u-strasbg.fr/PolyLib/

6.8. ORWL and P99

ORWL is a reference implementation of the Ordered Read-Write Lock tools as described in [1]. The macro definitions and tools for programming in C99 that have been implemented for ORWL have been separated out into a toolbox called P99. ORWL is intended to become opensource, once it will be in a publishable state. P99 is available under a QPL at http://p99.gforge.inria.fr/.

- Participants: Jens Gustedt, Mariem Saied, Daniel Salas
- Contact: Jens Gustedt
- http://p99.gforge.inria.fr/, http://orwl.gforge.inria.fr/

6.9. Stdatomic and Musl

We implement the library side of the C11 atomic interface. It needs compiler support for the individual atomic operations and provides library support for the cases where no low-level atomic instruction is available and a lock must be taken.

- This implementation builds entirely on the ABIs of the gcc compiler for atomics.
- It provide all function interfaces that the gcc ABIs and the C standard need.
- For compilers that don't offer the direct language support for atomics it provides a syntactically reduced but fully functional approach to atomic operations.
- At the core of the library is a new and very efficient futex-based lock algorithm that is implemented for the Linux operating system.

A description of the new lock algorithm has been given in [2]. A short version of it has been presented at SAC'16.

The primary target of this library is an integration into musl to which we also contribute. It is a re-implementation of the C library as it is described by the C and POSIX standards. It is *lightweight*, *fast*, *simple*, *free*, and strives to be correct in the sense of standards-conformance and safety. Musl is production quality code that is mainly used in the area of embedded device. It gains more market share also in other area, *e.g.* there are now Linux distributions that are based on musl instead of Gnu LibC.

- Participant: Jens Gustedt
- Contact: Jens Gustedt
- http://stdatomic.gforge.inria.fr/, http://www.musl-libc.org/

7. New Results

7.1. Formal Proofs about Happens-before in Explicitly Parallel Polyhedral Programs

Participants: Éric Violard, Alain Ketterlin.

Automatic parallelization has traditionally focused on sequential programs, but the widespread availability of explicitly parallel programming languages (such as OpenMP, Cilk, X10, and others) has led researchers to consider also the optimization and re-parallelization of parallel source programs. Most of these languages have constructions for parallel loops and parallel sections, with the accompanying synchronization primitives. The X10 language is especially interesting in this respect, because it provides simple and powerful constructions. Essentially, parallelism is expressed with the help of the `async` construct, whose body is to be executed in a parallel "activity", and the `finish` construct, which acts as a container for activities (and sub-activities) and waits for their completion. These constructions are complemented with "clocks", which are essentially synchronization barriers. Clocks can be used freely, in an unstructured manner, but are best associated with `finish` constructs, where they provide an intuitive and flexible phasing mechanism. In this case, activities spawned with `async` can either inherit or hide the clock provided by the nearest enclosing `finish`.

We are focusing on polyhedral programs, where all control is based on loops whose bounds are affine combinations of the enclosing loop counters and constant parameters. There is a large body of work on optimizing and parallelizing such programs, but most of them focus on sequential loop nests. Introducing X10's parallel constructions defines the class of *explicitly parallel polyhedral programs*, which is the focus of our work. Many polyhedral analyses and optimization techniques rely on the notion of lexicographic order, which is the order of execution of the statements in the source program. For instance, a data-dependence is defined to be an ordered pair of instruction instances that use or define the same data element, such that the first executes *before* the second. The lexicographic order is a purely syntactic characteristic that can be extracted from the source program. When the source program is explicitly parallel, the execution order becomes partial, because two distinct instruction instances can be part of concurrent activities. In this case the ordering is called the *Happens-before* relation. Paul Feautrier and Tomofumi Yuki have provided the first definition of *Happens-before* for explicitly parallel polyhedral programs, which covers the case of X10 programs using `finish` and `async` but without any clock involved. Being purely syntactic, their definition opens the way to the optimization of parallel X10 `finish`-`async` polyhedral programs. The use of clocks, however, introduces a major difficulty. Since clocks define phases of the program, one would like to use the "phase-number" of each instruction instance as an additional dimension, and include this dimension in further analysis. Phase-numbers have analytic forms (for the class of polyhedral programs), but they belong to the class of Ehrhart's quasi-polynomials, i.e., they are outside the polyhedral (affine) model.

We have formalized the class of programs under consideration, as well as all notions pertaining to the definition of the *Happens-before* relation, in Coq, a proof assistant developed at Inria. The formalization includes minimal structures to represent explicitly parallel polyhedral programs, including `finish` and `async`, loops, and simple statements. The definition of the *Happens-before* relation is that of an inductive predicate, parametrized by the computation of phase-numbers, which is left unspecified. To make the connection between the (static) *Happens-before* relation and the (dynamic) position of instruction instances in program traces, we use a single axiom. To reinforce our confidence in this arbitrary component, we also provide a second set of axioms, which we prove is equivalent to the first. The proof is based on an operational semantics, providing the relation between programs and their executions traces. We then prove that when *Happens-before* holds between two (static) instruction instances, then any trace of the program sees the corresponding dynamic instances ordered. We also prove the converse, which makes the definition of *Happens-before* sound and complete.

The Coq source files are kept in an Inria-forge project. Since this is our first effort in formal proofs, it currently amounts to about ten thousands lines of Coq source code. It is not yet clear whether we will publish the proof by itself, or publish an informal version of it as part of our colleagues' work on the use of *Happens-before*.

In any case, our short-term plan is to extend the formalization and accompanying theorems and proofs to the case of mixed-programs, where some activities ignore the clock in scope.

7.2. Loop Nests and Integer Polyhedra

Participant: Alain Ketterlin.

The polyhedral model has been found adequate to model a large number of program analyses and transformations. It has now been used for decades in automatic parallelization, locality optimization, high-level code synthesis, and other applications. Thanks to the availability of high-quality software tools, the polyhedral model is now widely used. However, we feel that some of its most fundamental operations need more thorough attention, and possibly new theoretical developments. Even though the translation of loop nests into polyhedra (or unions thereof) obviously use integers only, many algorithms still use an underlying rational (or real) domain. For instance, Fourier-Motzkin variable elimination is defined on rational domains, and its modern incarnation (the Omega test), uses convoluted and costly techniques to compensate for the mishandling of integer variables. When used for projection (for instance during code generation, i.e., turning polyhedra into loop nests), these defects lead to sub-optimal results, with programs including more control than necessary. Overall, we feel that current techniques are inadequate to capture the precise behavior of integer variables.

We have started investigating new representations for inequalities over integer variables, using a notation called “periodic numbers”. This notation was invented by Eugène Ehrhart in his classical results on the number of integer points inside integer polyhedra, and rediscovered and generalized by Philippe Clauss in his work on the use of counting for locality optimization and automatic parallelization. Periodic numbers capture all sorts of integer-specific behaviors: for instance, they are especially suitable to represent the seemingly chaotic structure of discrete line intersections, or the modular intersections of parallel hyper-planes. Periodic numbers also have algebraic properties that make them easy to manipulate and combine. We have defined a generalization of affine expressions where the constant term becomes a periodic number: it turns out that this family of expressions has interesting stability properties, that make them especially suitable for variable elimination. We have shown that most problems of Fourier-Motzkin variable elimination are related to the “looseness” of affine inequalities over integer variables, and that periodic numbers can correct this defect. The result is a new representation of inequalities, that makes reasoning with inequalities sound and complete.

An immediate application of our new representation is deciding whether a given integer polyhedron contains an integer point (or: whether a given set of affine constraints on integer variables is feasible). We have developed a straightforward version of Fourier-Motzkin elimination that is always exact. An interesting aspect of this work is that the algorithm is only a slight generalization of the original Fourier-Motzkin elimination, to cover the cases where inequalities have periodic components. We have also extended the basic algorithm to produce arbitrary projections of integer polyhedra. This improves over the Omega elimination strategy in that we are able to produce a provably disjoint union. These interesting properties derive directly from the use of periodic numbers.

Periodic numbers, and periodic linear inequalities, also have applications more directly related to the compilation of affine loop nests. For instance, we have developed a fully-general unswitching transformation. Unswitching a loop containing a conditional amounts to split the loop into one or more new loops such that the conditional has a constant truth value in all loop fragments, and can therefore be removed. The transformation is general in that the resulting program contains only affine loops and periodic linear conditionals. This means that the process can be repeated until obtaining a final version of the loop nest that is completely free of conditionals. We expect this “code generation” strategy, though naive, to remove enough “divergence” to increase existing and enable new applications of vectorization, leading to more efficient code. On the theory side, producing a conditional-free code scanning an arbitrary union of polyhedra has also direct consequences on various polyhedral operations: for instance, computing extrema becomes a trivial task, and linear optimization also falls under this umbrella. We hope to be able to explore these tracks in the near future.

We have developed software making use (and illustrating) our theoretical developments. We expect to share this software with select colleagues very soon, so as to be able to assess the scope of our techniques. Publication of these results is expected in the next year, time permitting. We also expect to extend our current software base to provide a range of integer polyhedra operations (images and pre-images, projection, and linear optimization, mostly). Finally, our middle-term goal is to investigate a formal modeling of the integer polyhedra operations. All algorithms have been kept as simple as possible, favoring elaborate abstractions over complex processing, with the goal of being able to formally specify the fundamental operations.

7.3. Splitting Polyhedra to Generate More Efficient Code

Participants: Harenome Ranaivoarivony-Razanajato, Vincent Loechner, Cédric Bastoul.

Code generation in the polyhedral model takes as input a union of Z-polyhedra and produces a code scanning all of them. Modern code generation tools are heavily relying on polyhedral operations to perform this task. However, these operations are typically provided by general-purpose polyhedral libraries that are not specifically designed to address the code generation problem. In particular, (unions of) polyhedra may be represented in various mathematically equivalent ways which may have different properties with respect to code generation. We investigated this problem and tried to find the best representation of polyhedra to generate an efficient code.

We demonstrated that this problem has been largely under-estimated, showing significant control overhead deviations when using different representations of the same polyhedra. Second, we proposed an improvement to the main algorithm of the state-of-the-art code generation tool CLooG. It generates code with less tests in the inner loops, and aims at reducing control overhead and at simplifying vectorization for the compiler, at the cost of a larger code size. It is based on a smart splitting of the union of polyhedra while recursing on the dimensions.

We implemented our algorithm in CLooG/PolyLib, and compared the performance and size of the generated code to the CLooG/isl version. Our results show that there can be important performance differences between the generated versions. In some cases, our new technique may significantly improve the quality of the generated code, but in some other cases, it may not be adequate compared to the existing solution. Finding other alternatives and chosing the best one remain open problems to be investigated in the future.

7.4. Code-Bones for Fast and Flexible Runtime Code Generation

Participants: Juan Manuel Martinez Caamaño, Artiom Baloian, Philippe Clauss.

We have developed a new runtime code generation technique for speculative loop optimization and parallelization. The main benefit of this technique, compared to previous approaches, is to enable advanced optimizing loop transformations at runtime with an acceptable time overhead. The loop transformations that may be applied are those handled by the polyhedral model. The proposed code generation strategy is based on the generation of *code-bones* at compile-time, which are parametrized code snippets either dedicated to speculation management or to computations of the original target program. These code bones are then instantiated and assembled at runtime to constitute the speculatively-optimized code, as soon as an optimizing polyhedral transformation has been determined. Their granularity threshold is sufficient to apply any polyhedral transformation, while still enabling fast runtime code generation. This approach has been implemented in the speculative loop parallelizing framework Apollo, and published at the conference Euro-Par 2016 where it has been selected as best paper [13]. An extended journal version is currently under review. This is also the main contribution of Juan Manuel Martinez Caamaño's PhD thesis which was defended in September 2016 [8].

7.5. Automatic Collapsing of Non-Rectangular Loops

Participants: Philippe Clauss, Ervin Altıntaş, Matthieu Kuhn.

Loop collapsing is a well-known loop transformation which combines some loops that are perfectly nested into one single loop. It allows to take advantage of the whole amount of parallelism exhibited by the collapsed loops, and provides a perfect load balancing of iterations among the parallel threads.

However, in the current implementations of this loop optimization, as the ones of the OpenMP language, automatic loop collapsing is limited to loops with constant loop bounds that define rectangular iteration spaces, although load imbalance is a particularly crucial issue with non-rectangular loops. The OpenMP language addresses load balance mostly through dynamic runtime scheduling of the parallel threads. Nevertheless, this runtime schedule introduces some unavoidable execution-time overhead, while preventing to exploit the entire parallelism of all the parallel loops.

We propose a technique to automatically collapse any perfectly nested loops defining non-rectangular iteration spaces, whose bounds are linear functions of the loop iterators. Such spaces may be triangular, tetrahedral, trapezoidal, rhomboidal or parallelepiped. Our solution is based on original mathematical results addressing the inversion of a multi-variate polynomial that defines a ranking of the integer points contained in a convex polyhedron.

We show on a set of non-rectangular loop nests that our technique allows to generate parallel OpenMP codes that outperform the original parallel loop nests, parallelized either by using options "static" or "dynamic" of the OpenMP-schedule clause. A conference paper presenting these results, co-authored by Philippe Clauss, Ervin Altıntaş (Master student) and Matthieu Kuhn (Inria Bordeaux Sud-Ouest, team HIEPACS), is currently under review.

7.6. Efficient Data Structures for a PIC Code on SIMD Architectures

Participants: Yann Barsamian, Éric Violard.

In collaboration with Sever Adrian Hirstoaga (mathematician researcher, member of Inria team TONUS), we have developed an efficient particle simulation code. The domain of application is plasma physics, the Particle-In-Cell code simulating 2d2v Vlasov-Poisson equation on Cartesian grid with periodic boundary conditions for Landau damping test-case. We first analyzed different strategies for improving its performance on single core and then we used a standard approach for parallelizing it on many cores using hybrid OpenMP/MPI implementation. The optimization of the sequential code is mainly based on (i) a structure of arrays for the particles, (ii) an efficient data structure for the electric field and the charge density, and (iii) an appropriate code for automatic vectorization of the charge accumulation and of the positions' update. The parallelization of the loops over the particles is performed in a simple way (without domain decomposition) by means of both distributed and share memory paradigms. Satisfactory strong and weak scaling up to 8,192 cores on GENCI's supercomputer Curie are obtained, bounded as expected by the overhead of MPI communications. A conference paper presenting this work is currently under review.

7.7. Interactive Code Restructuring

Participants: Cédric Bastoul, Oleksandr Zinenko, Stéphane Huot.

This work falls within the exploration and development of semi-automatic programs optimization techniques. It consists in designing and evaluating new visualization and interaction techniques for code restructuring, by defining and taking advantage of visual representations of the underlying mathematical model. The main goal is to assist programmers during program optimization tasks in a safe and efficient way, even if they neither have expertise into code restructuring nor knowledge of the underlying theories. This project is an important step for the efficient use and wider acceptance of semi-automatic optimization techniques, which are still tedious to use and incomprehensible for most programmers. More generally, this research is also investigating new presentation and manipulation techniques for code, algorithms and programs, which could lead to many practical applications: collaboration, tracking and verification of changes, visual search in large amount of code, teaching, etc.

This is a new research direction opened by CAMUS which strengthens the team's static parallelization and optimization issue. It is a joint work with two Inria teams specialized in interaction: EX-SITU at Inria Saclay (contact: Oleksandr Zinenko) and MJOLNIR at Inria Lille (contact: Stéphane Huot).

In 2016, we released the first version of our interactive tool, *Clint*, that maps direct manipulation of the visual representation to polyhedral program transformations with real-time semantics preservation feedback (https://ozinenko.com/clint). Oleksandr Zinenko also defended his thesis on the research and development on interactive code restructuring.

7.8. Automatic Generation of Adaptive Simulation Codes

Participants: Cédric Bastoul, Maxime Schmitt.

Compiler automatic optimization and parallelization techniques are well suited for some classes of simulation or signal processing applications, however they usually don't take into account neither domain-specific knowledge nor the possibility to change or to remove some computations to achieve "good enough" results. Quite differently, production simulation and signal processing codes have adaptive capabilities: they are designed to compute precise results only where it matters if the complete problem is not tractable or if the computation time must be short. In this research, we design a new way to provide adaptive capabilities to compute-intensive codes automatically, inspired by Adaptive Mesh Refinement a classical numerical analysis technique to achieve precise computation only in pertinent areas. It relies on domain-specific knowledge provided through special pragmas by the programmer in the input code and on polyhedral compilation techniques, to continuously regenerate at runtime a code that performs heavy computations only where it matters at every moment. A case study on a fluid simulation application shows that our strategy enables dramatic computation savings in the optimized portion of the application while maintaining good precision, with a minimal effort from the programmer.

This research direction started in 2015 and complements our other efforts on dynamic optimization. In 2016, we started a collaboration on this topic with Inria Nancy - Grand Est team TONUS, specialized on applied mathematics (contact: Philippe Helluy), to bring models and techniques from this field to compilers. This collaboration received the support from the excellence laboratory (LabEx) IRMIA through the funding of the thesis of Maxime Schmitt on this topic. A first paper on this new research direction has just been accepted to IMPACT 2017.

7.9. Polyhedral Compiler White-Boxing

Participants: Cédric Bastoul, Lénaïc Bagnères, Oleksandr Zinenko, Stéphane Huot.

While compilers offer a fair trade-off between productivity and executable performance in single-threaded execution, their optimizations remain fragile when addressing compute-intensive code for parallel architectures with deep memory hierarchies. Moreover, these optimizations operate as black boxes, impenetrable for the user, leaving them with no alternative to time-consuming and error-prone manual optimization in cases where an imprecise cost model or a weak analysis resulted in a bad optimization decision. To address this issue, we researched and designed a technique allowing to automatically translate an arbitrary polyhedral optimization, used internally by loop-level optimization frameworks of several modern compilers, into a sequence of comprehensible syntactic transformations as long as this optimization focuses on scheduling loop iterations. With our approach, we open the black box of the polyhedral frameworks enabling users to examine, refine, replay and even design complex optimizations semi-automatically in partnership with the compiler.

This research started in 2014 and we published our first solution in 2016. It has been conducted as a joint work between teams in compiler technologies (CAMUS and Inria Saclay's POSTALE team) and teams in interaction (EX-SITU at Inria Saclay and MJOLNIR at Inria Lille). The first paper on this has been accepted and presented in one of the top conferences on optimization techniques: CGO 2016 [10]. It is also discussed in Lénaïc Bagnèse and Oleksandr Zinenko theses. In 2016 we finally release the tool implementing this research (https://periscop.github.io/chlore).

7.10. Mapping Deviation

Participant: Cédric Bastoul.

Compilers can provide a major help by automating the optimization and parallelization work. However they are very fragile black-boxes. A compiler may take a bad optimization decision because of imprecise heuristics or may turn off an optimization because of imprecise analyses, without providing much control or feedback to the end user. To address this issue, we researched and introduced mapping deviation, a new compiler technique that aims at providing a useful feedback on the semantics of a given program restructuring. Starting from a transformation intuition a user or a compiler wants to apply, our algorithm studies its correctness and can suggest changes or conditions to make it possible rather than being limited to the classical go/no-go answer. This algorithm builds on state-of-the-art polyhedral representation of programs and provides a high flexibility. We present two example applications of this technique: improving semi-automatic optimization tools for programmers and automatically designing runtime tests to check the correctness of a transformation for compilers.

This is a mid-term research on the mathematical ground of polyhedral compilation, started back to 2012. We found a solution and published it in 2016 in one of the main conferences in compilation: Compiler Construction [11]. We plan to release the tool that implements this research during the coming year.

7.11. Combining Locking and Data Management Interfaces

Participants: Jens Gustedt, Mariem Saied, Daniel Salas.

Handling data consistency in parallel and distributed settings is a challenging task, in particular if we want to allow for an easy to handle asynchronism between tasks. Our publication [1] shows how to produce deadlock-free iterative programs that implement strong overlapping between communication, IO and computation.

An implementation (ORWL) of our ideas of combining control and data management in C has been undertaken, see 6.8. In previous work it has demonstrated its efficiency for a large variety of platforms. In 2016, work on the ORWL model and library has gained vigor with the thesis of Mariem Saied (Inria & University of Strasbourg) and Daniel Salas (INSERM). We also now collaborate on that subject with the TADAAM project team from Inria Bordeaux, where a postdoc has been hired through Inria funding.

In 2016, a new domain specific language (DSL) has been completed that largely eases the implementation of applications with ORWL. In its first version it provides an interface for stencil codes, but extensions towards other types of applications are on their way. The approach allows to describe stencil codes quickly and efficient and leads to substantial speedups, see [14].

In addition, the framework has successfully been applied to encapsulate imaging applications that use certain pipeline patterns to describe dependencies between computational tasks, see [16]. Generally we have been able to use the knowledge of the communication structure of ORWL programs to map tasks to cores and thereby achieve interesting performance gains on multicore architectures, see [20].

In another work we have successfully applied ORWL to process Large Histopathology Images, see [15].

8. Bilateral Contracts and Grants with Industry

8.1. Caldera

Vincent Loechner and Cédric Bastoul are involved in a collaboration with the French company Caldera (http://www.caldera.com), specialized in software development for wide image processing. The goal of this collaboration is the development of parallel and scalable image processing pipeline for industrial printing. The project started in September 2016 and involves a contract established between the ICube laboratory and the Caldera company. This contract includes the funding of the industrial thesis (CIFRE) of Paul Godard (started in September 2016) on the topic of the collaboration, under the supervision of Vincent Loechner and Cédric Bastoul.

8.2. NANO 2017/PSAIC

The CAMUS team is taking part of the NANO 2017 national research program and its sub-project PSAIC (Performance and Size Auto-tuning thru Iterative Compilation) with the company STMicroelectronics, starting January 2015. Since the release of our automatic speculative parallelization framework Apollo, we have been working on an extension making Apollo usable as a advanced program profiling tool. We are also currently working in extending advanced loop optimization techniques to nonlinear loops using a linear virtual data layout remapping.

9. Partnerships and Cooperations

9.1. National Initiatives

Philippe Clauss, Alain Ketterlin, Cédric Bastoul and Vincent Loechner are involved in the Inria Project Lab entitled "Large scale multicore virtualization for performance scaling and portability" and regrouping several french researchers in compilers, parallel computing and program optimization [0]. The project started officially in January 2013. In this context and since January 2013, Philippe Clauss is co-advising with Erven Rohou of the Inria team PACAP, Nabil Hallou's PhD thesis focusing on dynamic optimization of binary code.

9.2. International Initiatives

9.2.1. Inria International Partners

9.2.1.1. Informal International Partners

The CAMUS team maintains regular contacts with the following entities:

- Reservoir Labs, New York, NY, USA
- University of Batna, Algeria
- Ohio State University, Colombus, USA
- Louisiana State University, Baton Rouge, USA
- Colorado State University, Fort Collins, USA
- Indian Institute of Science (IIIS) Bangalore, India

9.3. International Research Visitors

9.3.1. Visits of International Scientists

9.3.1.1. Researchers

Rachid Seghir

Date: April 30 - May 14

Institution: University of Batna, Algeria

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Selection

10.1.1.1. Member of the Conference Program Committees

Cédric Bastoul has been part of the program committee of IMPACT 2016 (International Workshop on Polyhedral Compilation Techniques), held in conjunction with the international conference HiPEAC 2016.

[0] https://team.inria.fr/multicore

Philippe Clauss and Cédric Bastoul have been part of the program committee of IMPACT 2017 (International Workshop on Polyhedral Compilation Techniques), held in conjunction with the international conference HiPEAC 2017.

Alain Ketterlin has been part of the program committee of CGO 2016 (International Symposium on Code Generation and Optimization, http://cgo.org/cgo2016).

Cédric Bastoul and Vincent Loechner have been part of the program committee of both HIP3ES 2016 and HIP3ES 2017 (International Workshop on High Performance Energy Efficient Embedded Systems), held in conjunction with the international conference HiPEAC 2016 (resp. HiPEAC 2017).

Cédric Bastoul has been part of the program committee of PARMA+DITAM 2016 and PARMA+DITAM 2017 (Workshop on Parallel Programming and Run-Time Management Techniques for Many-core Architectures + Workshop on Design Tools and Architerctures for Multicore Embedded Computing Platforms), held in conjunction with HiPEAC 2016 (resp. HiPEAC 2017).

Cédric Bastoul has been part of the program committee of the international conference on Compiler Construction 2017 (CC'2017).

10.1.1.2. Reviewer

Philippe Clauss has been reviewer for the following conferences and workshops: IMPACT 2017 (International Workshop on Polyhedral Compilation Techniques), CC 2017 (International Conference on Compiler Construction).

Cédric Bastoul has been reviewer for the following international conferences and workshops: CC 2017 (International Conference on Compiler Construction), PARMA 2016 and 2017 (International Workshop on Parallel Programming and Run-Time Management Techniques for Many-core Architectures), IMPACT 2016 and 2017 (International Workshop on Polyhedral Compilation Techniques), HIP3ES 2016 and 2017 (International Workshop on High Performance Energy Efficient Embedded Systems).

Vincent Loechner has been reviewer for CC 2017 (International Conference on Compiler Construction), HIP3ES 2016 and 2017 (International Workshop on High Performance Energy Efficient Embedded Systems).

10.1.2. Journal

10.1.2.1. Member of the Editorial Boards

Since October 2001, J. Gustedt is Editor-in-Chief of the journal *Discrete Mathematics and Theoretical Computer Science* (DMTCS).

10.1.2.2. Reviewer - Reviewing Activities

Philippe Clauss has been reviewer for the following journals: ACM TACO (Transactions on Architecture and Code Optimization), Parallel Computing.

Cédric Bastoul has been reviewer for the *ACM Transactions on Parallel Computing International Journal* (TOPC).

Jens Gustedt has been reviewer for Theory of Computing Systems.

Vincent Loechner has been reviewer for *Computer Communications* (Elsevier).

10.1.3. Invited Talks

Philippe Clauss has been invited to present the framework Apollo at the Parallel Programming Laboratory of the University of Darmstadt, Germany, October the 28th.

Philippe Clauss has presented the framework Apollo at the COSI research group of the Colorado State University, Fort Collins, USA, July the 1st.

10.1.4. Scientific Expertise

Cédric Bastoul as been an expert for the French research ministry and the French finance ministry for the research tax credit programme.

Jens Gustedt served as expert for project evaluation for the Belgian FNRS, and as evaluator of the FEMTO-ST Lab, Besançon, for the French HCERES.

10.1.5. Standardization

Since Nov. 2014, Jens Gustedt is a member of the ISO working group SC22-WG14 for the standardization of the C programming language. He participates actively in the defect report processing, the planning of future versions of the standard, and publishes an ongoing document to track inconsistencies and improvements of the C threads interface.

This work on the C programming language also gave rise to the proposal of a language extension, Modular C. It has been used for the implementation of an efficient toolbox for *higher order automatic differenciation*, `arbogast`, see [18] and [19], which has been presented at the quadrennial conference of the domain, AD2016.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Licence : Philippe Clauss, Architecture des ordinateurs, 45h, Université de Strasbourg, France

Licence : Philippe Clauss, Systèmes d'exploitation, 40h, Université de Strasbourg, France

Master : Philippe Clauss, Compilation, 78h, Université de Strasbourg, France

Master : Philippe Clauss, Système et programmation temps-réel, 25h, Université de Strasbourg, France

Master : Philippe Clauss, Compilation avancée, 30h, Université de Strasbourg, France

Licence : Éric Violard, Programmation Fonctionnelle (licence informatique), 64h eq. TD, L2, Université de Strasbourg, France

Licence : Éric Violard, Architecture des Ordinateurs (licence informatique), 54h eq. TD, L2, Université de Strasbourg, France

Licence : Éric Violard, Logique et Programmation Logique (licence informatique), 34h eq. TD, L2, Université de Strasbourg, France

Licence : Éric Violard, Algorithmique et Structures de Données (licence mathématique), 39h eq. TD, L3, Université de Strasbourg, France

Licence : Éric Violard, Modèles de Calcul (licence informatique), 29h eq. TD, L1, Université de Strasbourg, France

Licence : Vincent Loechner, Systèmes d'exploitation, 51h, L2, Université de Strasbourg, France

Master : Vincent Loechner, parallélisme, 14h, M1, Université de Strasbourg, France

Master : Vincent Loechner, calcul parallèle, 32h, M1, Université de Strasbourg, France

Master : Vincent Loechner, langages interprétés, 37h, M1, Université de Strasbourg, France

Master : Vincent Loechner, OS embarqués, 31h, M2, Université de Strasbourg, France

Telecom Physique Strasbourg : Vincent Loechner, calcul parallèle, 20h, M2, Université de Strasbourg, France

Licence : Alain Ketterlin, Systèmes d'exploitation, 20h, Université de Strasbourg, France

Licence : Alain Ketterlin, Systèmes Concurrents, 24h, Université de Strasbourg, France

Licence : Alain Ketterlin, Réseaux et protocoles, 42h, Université de Strasbourg, France

Master : Alain Ketterlin, Compilation, 26h, Université de Strasbourg, France

Licence : Cédric Bastoul, Architecture, 68h, L1 (IUT), Université de Strasbourg, France

Licence : Cédric Bastoul, Operating Systems, 16h, L2, Université de Strasbourg, France

Licence : Cédric Bastoul, Concurrent Systems, 19h, L3, Université de Strasbourg, France

Master : Cédric Bastoul, Compiler Design, 48h, M1, Université de Strasbourg, France

Master : Cédric Bastoul, Parallelism, 16h, M1, Université de Strasbourg, France

Master : Cédric Bastoul, Introduction to Research, 7h, L3+M1, Université de Strasbourg, France

2nd year engineering school: Jens Gustedt, programmation avancée, 20h, ENSIIE Strasbourg, France

Licence : Jens Gustedt, systèmes concurrents, 20h, Université de Strasbourg, France

10.2.2. Supervision

PhD: Tomasz Buchert, Madynes team, *Orchestration of experiments on distributed systems*, since Oct 2011, defended on Jan 6 2016, Jens Gustedt & Lucas Nussbaum.

PhD: Juan Manuel Martinez Caamaño, *Fast and Flexible Compilation Techniques for Effective Speculative Polyhedral Parallelization*, September 29th 2016, Philippe Clauss and Philippe Helluy (IRMA lab., University of Strasbourg)

PhD: Michel Massaro, *Méthodes numériques pour les plasmas sur architectures multicœurs*, December 16th 2016, Philippe Helluy and Vincent Loechner

PhD: Lénaïc Bagnères, Adaptation automatique et semi-automatique des optimisations de programmes, September 30$^{\text{th}}$, Christine Eisenbeis and Cédric Bastoul

PhD: Olexander Zinenko, Interactive Program Restructuring, November 25$^{\text{th}}$ 2016, Stéphane Huot and Cédric Bastoul

PhD in progress: Yann Barsamian, *Optimization and parallelization of particle and semi-Lagrangian methods for multi species plasma simulations*, since Oct 2014, Éric Violard

PhD in progress: Mariem Saied, *Ordered Read-Write Locks for Multicores and Accelerators*, since Nov 2013, Jens Gustedt & Gilles Muller.

PhD in progress: Daniel Salas, *Integration of the ORWL model into parallel applications for medical research*, since Mar 2015, Jens Gustedt & Isabelle Perseil.

PhD in progress: Nabil Hallou, *Dynamic binary optimizations*, since January 2013, Erven Rohou (PACAP team) and Philippe Clauss

PhD in progress: Harenome Ranaivoarivony-Razanajato, *Hierarchical Optimization and Parallelization*, September 2016, Vincent Loechner and Philippe Clauss

PhD in progress: Maxime Schmitt, *Automatic Generation of Adaptive Codes*, September 2016, Cédric Bastoul and Philippe Helluy

PhD in progress: Paul Godard, *Parallelization and Scalability of an Image Processing Pipeline for Professional Printing*, September 2016, Vincent Loechner and Cédric Bastoul

10.2.3. Juries

Philippe Clauss participated to the following PhD committees in 2016:

Date	**Candidate**	**Place**	**Role**
Jun. 30	Guillaume Iooss	Colorado State Univ., USA	Reviewer
Oct. 28	Zhen Li	Univ. Darmstadt, Germany	Reviewer
Sept. 29	Juan Manuel Martinez Caamaño	Univ. Strasbourg	Advisor
Dec. 14	Julien Pagès	Univ. Montpellier	Reviewer

Cédric Bastoul participated to the following PhD committees in 2016:

Date	**Candidate**	**Place**	**Role**
June 22	Abdul Memon	Paris-Saclay University	Reviewer
September 30	Lénaïc Bagnères	Paris-Saclay University	Advisor
November 18	Albert Saa	Universitat Autònoma de Barcelona	Reviewer
November 25	Oleksandr Zinenko	Paris-Saclay University	Advisor
November 30	Pierre Guillou	Paris Sciences et Lettres Research University	Reviewer

Vincent Loechner participated to the following PhD committees in 2016:

Date	**Candidate**	**Place**	**Role**
May 10	Arjun Suresh	Univ. Rennes 1	Examiner
December 16	Michel Massaro	Univ. Strasbourg	Co-advisor

Vincent Loechner was the president of the recruiting jury (*comité de sélection*) for an assistant professor position at the Department of Mathematics and Computer Science of the University of Strasbourg, during Spring 2016.

10.3. Popularization

Jens Gustedt is regularly blogging about efficient programming, in particular about the C programming language. He also is an active member of the stackoverflow community a technical Q&A site for programming and related subjects. A first complete online version of his book *Modern C*, to appear in 2017, has been accessed more than 10000 times on a single day.

11. Bibliography

Major publications by the team in recent years

[1] P.-N. Clauss, J. Gustedt.*Iterative Computations with Ordered Read-Write Locks*, in "Journal of Parallel and Distributed Computing", 2010, vol. 70, n^{o} 5, p. 496-504 [*DOI :* 10.1016/j.jpdc.2009.09.002], https://hal.inria.fr/inria-00330024.

[2] J. Gustedt.*Futex based locks for C11's generic atomics*, Inria Nancy, December 2015, n^{o} RR-8818, https://hal.inria.fr/hal-01236734.

[3] A. Jimborean, P. Clauss, J.-F. Dollinger, V. Loechner, M. Juan Manuel.*Dynamic and Speculative Polyhedral Parallelization Using Compiler-Generated Skeletons*, in "International Journal of Parallel Programming", August 2014, vol. 42, n^{o} 4, p. 529-545, https://hal.inria.fr/hal-01003744.

[4] A. Ketterlin, P. Clauss.*Prediction and trace compression of data access addresses through nested loop recognition*, in "6th annual IEEE/ACM international symposium on Code generation and optimization", Boston, USA, ACM, April 2008, p. 94-103, http://dx.doi.org/10.1145/1356058.1356071.

[5] A. Ketterlin, P. Clauss.*Profiling Data-Dependence to Assist Parallelization: Framework, Scope, and Optimization*, in "MICRO-45 – Proceedings of the 2012 IEEE/ACM 45th International Symposium on Microarchitecture", Vancouver, Canada, December 2012.

[6] B. Pradelle, A. Ketterlin, P. Clauss.*Polyhedral parallelization of binary code*, in "ACM Transactions on Architecture and Code Optimization", January 2012, vol. 8, n^{o} 4, p. 39:1–39:21 [*DOI :* 10.1145/2086696.2086718], http://hal.inria.fr/hal-00664370.

[7] R. Seghir, V. Loechner, B. Meister.*Integer Affine Transformations of Parametric Z-polytopes and Applications to Loop Nest Optimization*, in "ACM Transactions on Architecture and Code Optimization", June 2012, vol. 9, n^{o} 2, p. 8.1-8.27 [*DOI :* 10.1145/2207222.2207224], http://hal.inria.fr/inria-00582388.

Publications of the year

Doctoral Dissertations and Habilitation Theses

[8] J. M. MARTINEZ CAAMAÑO.*Fast and Flexible Compilation Techniques for Effective Speculative Polyhedral Parallelization*, Université de Strasbourg, September 2016, https://hal.inria.fr/tel-01377758.

Articles in International Peer-Reviewed Journal

[9] A. SUKUMARAN-RAJAM, P. CLAUSS.*The Polyhedral Model of Nonlinear Loops*, in "ACM Transactions on Architecture and Code Optimization", January 2016, vol. 12, n^{o} 4 [*DOI :* 10.1145/2838734], https://hal.inria.fr/hal-01244464.

International Conferences with Proceedings

[10] L. BAGNÈRES, O. ZINENKO, S. HUOT, C. BASTOUL.*Opening Polyhedral Compiler's Black Box*, in "CGO 2016 - 14th Annual IEEE/ACM International Symposium on Code Generation and Optimization", Barcelona, Spain, March 2016, https://hal.inria.fr/hal-01253322.

[11] C. BASTOUL.*Mapping Deviation: A Technique to Adapt or to Guard Loop Transformation Intuitions for Legality*, in "CC'2016 25th International Conference on Compiler Construction", Barcelone, Spain, March 2016, https://hal.inria.fr/hal-01271998.

[12] J. GUSTEDT.*Futex based locks for C11's generic atomics (extended abstract)*, in "The 31st Annual ACM Symposium on Applied Computing", Pisa, Italy, April 2016 [*DOI :* 10.1145/2851613.2851956], https://hal.inria.fr/hal-01304108.

[13] *Best Paper*
J. M. MARTINEZ CAAMAÑO, W. WOLFF, P. CLAUSS.*Code Bones: Fast and Flexible Code Generation for Dynamic and Speculative Polyhedral Optimization*, in "Euro-Par 2016", Grenoble, France, SPRINGER-VERLAG (editor), Proceedings of the 22nd International Conference Euro-Par 2016: Parallel Processing, August 2016, vol. 9833, 12 [*DOI :* 10.1007/978-3-319-43659-3_17], https://hal.inria.fr/hal-01377656.

[14] M. SAIED, J. GUSTEDT, G. MULLER.*Automatic Code Generation for Iterative Multi-dimensional Stencil Computations*, in "High Performance Computing, Data, and Analitics", Hydarabat, India, A. BENOÎT (editor), IEEE, December 2016, https://hal.inria.fr/hal-01337093.

[15] D. SALAS, J. GUSTEDT, D. RACOCEANU, I. PERSEIL.*Resource-Centered Distributed Processing of Large Histopathology Images*, in "19th IEEE International Conference on Computational Science and Engineering", Paris, France, August 2016, https://hal.inria.fr/hal-01325648.

National Conferences with Proceeding

[16] F. MANSOURI, J. GUSTEDT.*Le modèle de programmation ORWL pour la parallélisation d'une application de suivi vidéo HD sur architecture multi-coeurs*, in "Conférence d'informatique en Parallélisme, Architecture et Système (COMPAS)", Lorient, France, July 2016, accepted for publication in Compas'16, https://hal.inria.fr/hal-01325850.

Scientific Books (or Scientific Book chapters)

[17] S. LEILA HERNANE, J. GUSTEDT.*Transparent distributed data management in large scale distributed systems*, in "Pervasive Computing", Academic Press, 2016, p. 153-194, https://hal.inria.fr/hal-01308989.

Research Reports

[18] I. CHARPENTIER, J.-P. FRIEDELMEYER, J. GUSTEDT.*Arbogast – Origine d'un outil de dérivation automatique*, Inria, May 2016, n^o RR-8911, https://hal.inria.fr/hal-01313355.

[19] I. CHARPENTIER, J. GUSTEDT.*Arbogast Higher order AD for special functions with Modular C*, Inria Nancy - Grand Est (Villers-lès-Nancy, France), April 2016, n^o 8907, https://hal.inria.fr/hal-01307750.

[20] J. GUSTEDT, E. JEANNOT, F. MANSOURI.*Fully-abstracted affinity optimization for task-based models*, Inria Nancy, December 2016, n^o RR-8993, https://hal.inria.fr/hal-01409101.

Other Publications

[21] J. GUSTEDT, E. JEANNOT, F. MANSOURI.*Optimizing Locality by Topology-aware Placement for a Task Based Programming Model*, September 2016, p. 164 - 165, IEEE Cluster 2016 Conference, Poster [*DOI :* 10.1109/CLUSTER.2016.87], https://hal.archives-ouvertes.fr/hal-01416284.

[22] O. ZINENKO, S. HUOT, C. BASTOUL.*Interactive Program Restructuring*, November 2016, working paper or preprint, https://hal.inria.fr/hal-01406294.

References in notes

[23] C. BASTOUL.*Code Generation in the Polyhedral Model Is Easier Than You Think*, in "PACT'13 IEEE International Conference on Parallel Architecture and Compilation Techniques", Juan-les-Pins, France, 2004, p. 7–16, https://hal.archives-ouvertes.fr/ccsd-00017260.

[24] M. HALL, D. PADUA, K. PINGALI.*Compiler research: the next 50 years*, in "Commun. ACM", 2009, vol. 52, n^o 2, p. 60–67, http://doi.acm.org/10.1145/1461928.1461946.

[25] A. HOBOR, A. W. APPEL, F. Z. NARDELLI.*Oracle Semantics for Concurrent Separation Logic*, in "ESOP", 2008, p. 353-367.

Project-Team CAPSID

Computational Algorithms for Protein Structures and Interactions

IN COLLABORATION WITH: Laboratoire lorrain de recherche en informatique et ses applications (LORIA)

IN PARTNERSHIP WITH:
CNRS

Université de Lorraine

RESEARCH CENTER
Nancy - Grand Est

THEME
Computational Biology

Table of contents

Project-Team CAPSID

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

Keywords:

Computer Science and Digital Science:

1.5.1. - Systems of systems
3.1.1. - Modeling, representation
3.2.2. - Knowledge extraction, cleaning
3.2.5. - Ontologies
6.1.5. - Multiphysics modeling

Other Research Topics and Application Domains:

1.1.1. - Structural biology
1.1.2. - Molecular biology
1.1.9. - Bioinformatics
2.2.1. - Cardiovascular and respiratory diseases
2.2.4. - Infectious diseases, Virology

1. Members

Research Scientists

David Ritchie [Team leader, Inria, Senior Researcher, HDR]
Isaure Chauvot de Beauchêne [CNRS, Researcher, from Dec 2016]
Marie-Dominique Devignes [CNRS, Researcher, HDR]
Bernard Maigret [CNRS, Senior Researcher, HDR]

Faculty Member

Sabeur Aridhi [Univ. Lorraine, Associate Professor, from Sep 2016]

Technical Staff

Antoine Chemardin [Inria]

PhD Students

Seyed Ziaeddin Alborzi [Inria]
Gabin Personeni [Univ. Lorraine]
Maria Elisa Ruiz Echartea [Inria, from Nov 2016]

Administrative Assistants

Emmanuelle Deschamps [Inria]
Laurence Félicité [Univ. Lorraine]
Christelle Levêque [Univ. Lorraine]

Others

Jessica Cummins [Univ. Dublin, Student, from Apr 2016 until Aug 2016]
Pierre Daudier de Cassini [INSERM, Student, from Apr 2016 until Jun 2016]
Marwa El Houasli [Univ. Paris 7, Student, from Apr 2016 until Aug 2016]
Valerian Gonnot [CPP-INP, Student, from May 2016 until Jun 2016]
Maxime Guyot [INSERM, Student, from May 2016 until Aug 2016]
Vincent Leroux [Univ. Lorraine, Visiting Scientist, from Apr 2016 until Dec 2016]
Zacharie Mehnana [CNRS, Student, from Jun 2016 until Aug 2016]

2. Overall Objectives

2.1. Computational Challenges in Structural Biology

Many of the processes within living organisms can be studied and understood in terms of biochemical interactions between large macromolecules such as DNA, RNA, and proteins. To a first approximation, DNA and RNA may be considered to encode the blueprint for life, whereas proteins make up the three-dimensional (3D) molecular machinery. Many biological processes are governed by complex systems of proteins which interact cooperatively to regulate the chemical composition within a cell or to carry out a wide range of biochemical processes such as photosynthesis, metabolism, and cell signalling, for example. It is becoming increasingly feasible to isolate and characterise some of the individual protein components of such systems, but it still remains extremely difficult to achieve detailed models of how these complex systems actually work. Consequently, a new multidisciplinary approach called integrative structural biology has emerged which aims to bring together experimental data from a wide range of sources and resolution scales in order to meet this challenge [69], [53].

Understanding how biological systems work at the level of 3D molecular structures presents fascinating challenges for biologists and computer scientists alike. Despite being made from a small set of simple chemical building blocks, protein molecules have a remarkable ability to self-assemble into complex molecular machines which carry out very specific biological processes. As such, these molecular machines may be considered as complex systems because their properties are much greater than the sum of the properties of their component parts.

The overall objective of the Capsid team is to develop algorithms and software to help study biological systems and phenomena from a structural point of view. In particular, the team aims to develop algorithms which can help to model the structures of large multi-component biomolecular machines and to develop tools and techniques to represent and mine knowledge of the 3D shapes of proteins and protein-protein interactions. Thus, a unifying theme of the team is to tackle the recurring problem of representing and reasoning about large 3D macromolecular shapes. More specifically, our aim is to develop computational techniques to represent, analyse, and compare the shapes and interactions of protein molecules in order to help better understand how their 3D structures relate to their biological function. In summary, the Capsid team focuses on the following closely related topics in structural bioinformatics:

- new approaches for knowledge discovery in structural databases,
- integrative multi-component assembly and modeling.

As indicated above, structural biology is largely concerned with determining the 3D atomic structures of proteins, and then using these structures to study their biological properties and interactions. Each of these activities can be extremely time-consuming. Solving the 3D structure of even a single protein using X-ray crystallography or nuclear magnetic resonance (NMR) spectroscopy can often take many months or even years of effort. Even simulating the interaction between two proteins using a detailed atomistic molecular dynamics simulation can consume many thousands of CPU-hours. While most X-ray crystallographers, NMR spectroscopists, and molecular modelers often use conventional sequence and structure alignment tools to help propose initial structural models through the homology principle, they often study only individual structures or interactions at a time. Due to the difficulties outlined above, only relatively few research groups are able to solve the structures of large multi-component systems.

Similarly, most current algorithms for comparing protein structures, and especially those for modeling protein interactions, work only at the pair-wise level. Of course, such calculations may be accelerated considerably by using dynamic programming (DP) or fast Fourier transform (FFT) techniques. However, it remains extremely challenging to scale up these techniques to model multi-component systems. For example, the use of high performance computing (HPC) facilities may be used to accelerate arithmetically intensive shape-matching calculations, but this generally does not help solve the fundamentally combinatorial nature of many multi-component problems. It is therefore necessary to devise heuristic hybrid approaches which can be tailored to exploit various sources of domain knowledge. We therefore set ourselves the following main computational objectives:

- classify and mine protein structures and protein-protein interactions,
- develop multi-component assembly techniques for integrative structural biology.

3. Research Program

3.1. Classifying and Mining Protein Structures and Protein Interactions

3.1.1. Context

The scientific discovery process is very often based on cycles of measurement, classification, and generalisation. It is easy to argue that this is especially true in the biological sciences. The proteins that exist today represent the molecular product of some three billion years of evolution. Therefore, comparing protein sequences and structures is important for understanding their functional and evolutionary relationships [66], [44]. There is now overwhelming evidence that all living organisms and many biological processes share a common ancestry in the tree of life. Historically, much of bioinformatics research has focused on developing mathematical and statistical algorithms to process, analyse, annotate, and compare protein and DNA sequences because such sequences represent the primary form of information in biological systems. However, there is growing evidence that structure-based methods can help to predict networks of protein-protein interactions (PPIs) with greater accuracy than those which do not use structural evidence [48], [71]. Therefore, developing techniques which can mine knowledge of protein structures and their interactions is an important way to enhance our knowledge of biology [34].

3.1.2. Quantifying Structural Similarity

Often, proteins may be divided into modular sub-units called domains, which can be associated with specific biological functions. Thus, a protein domain may be considered as the evolutionary unit of biological structure and function [70]. However, while it is well known that the 3D structures of protein domains are often more evolutionarily conserved than their one-dimensional (1D) amino acid sequences, comparing 3D structures is much more difficult than comparing 1D sequences. However, until recently, most evolutionary studies of proteins have compared and clustered 1D amino acid and nucleotide sequences rather than 3D molecular structures.

A pre-requisite for the accurate comparison of protein structures is to have a reliable method for quantifying the structural similarity between pairs of proteins. We recently developed a new protein structure alignment program called Kpax which combines an efficient dynamic programming based scoring function with a simple but novel Gaussian representation of protein backbone shape [59]. This means that we can now quantitatively compare 3D protein domains at a similar rate to throughput to conventional protein sequence comparison algorithms. We recently compared Kpax with a large number of other structure alignment programs, and we found Kpax to be the fastest and amongst the most accurate, in a CATH family recognition test [50]. The latest version of Kpax [20] can calculate multiple flexible alignments, and thus promises to avoid such issues when comparing more distantly related protein folds and fold families.

3.1.3. Formalising and Exploiting Domain Knowledge

Concerning protein structure classification, we aim to explore novel classification paradigms to circumvent the problems encountered with existing hierarchical classifications of protein folds and domains. In particular it will be interesting to set up fuzzy clustering methods taking advantage of our previous work on gene functional classification [36], but instead using Kpax domain-domain similarity matrices. A non-trivial issue with fuzzy clustering is how to handle similarity rather than mathematical distance matrices, and how to find the optimal number of clusters, especially when using a non-Euclidean similarity measure. We will adapt the algorithms and the calculation of quality indices to the Kpax similarity measure. More fundamentally, it will be necessary to integrate this classification step in the more general process leading from data to knowledge called Knowledge Discovery in Databases (KDD) [40].

Another example where domain knowledge can be useful is during result interpretation: several sources of knowledge have to be used to explicitly characterise each cluster and to help decide its validity. Thus, it will be useful to be able to express data models, patterns, and rules in a common formalism using a defined vocabulary for concepts and relationships. Existing approaches such as the Molecular Interaction (MI) format [45] developed by the Human Genome Organization (HUGO) mostly address the experimental wet lab aspects leading to data production and curation [55]. A different point of view is represented in the Interaction Network Ontology (INO; http://www.ino-ontology.org/) which is a community-driven ontology that is being developed to standardise and integrate data on interaction networks and to support computer-assisted reasoning [72]. However, this ontology does not integrate basic 3D concepts and structural relationships. Therefore, extending such formalisms and symbolic relationships will be beneficial, if not essential, when classifying the 3D shapes of proteins at the domain family level.

3.1.4. 3D Protein Domain Annotation and Shape Mining

A widely used collection of protein domain families is "Pfam" [39], constructed from multiple alignments of protein sequences. Integrating domain-domain similarity measures with knowledge about domain binding sites, as introduced by us in our KBDOCK approach [1], [3], can help in selecting interesting subsets of domain pairs before clustering. Thanks to our KBDOCK and Kpax projects, we already have a rich set of tools with which we can start to process and compare all known protein structures and PPIs according to their component Pfam domains. Linking this new classification to the latest "SIFTS" (Structure Integration with Function, Taxonomy and Sequence) [67] functional annotations between standard Uniprot (http://www.uniprot.org/ sequence identifiers and protein structures from the Protein Data Bank (PDB) [33] could then provide a useful way to discover new structural and functional relationships which are difficult to detect in existing classification schemes such as CATH or SCOP. As part of the thesis project of Seyed Alborzi, we have developed a recommender-based data mining technique to associate enzyme classification code numbers with Pfam domains using our recently developed EC-DomainMiner program [29].

3.2. Integrative Multi-Component Assembly and Modeling

3.2.1. Context

At the molecular level, each PPI is embodied by a physical 3D protein-protein interface. Therefore, if the 3D structures of a pair of interacting proteins are known, it should in principle be possible for a docking algorithm to use this knowledge to predict the structure of the complex. However, modeling protein flexibility accurately during docking is very computationally expensive due to the very large number of internal degrees of freedom in each protein, associated with twisting motions around covalent bonds. Therefore, it is highly impractical to use detailed force-field or geometric representations in a brute-force docking search. Instead, most protein docking algorithms use fast heuristic methods to perform an initial rigid-body search in order to locate a relatively small number of candidate binding orientations, and these are then refined using a more expensive interaction potential or force-field model, which might also include flexible refinement using molecular dynamics (MD), for example.

3.2.2. Polar Fourier Docking Correlations

In our *Hex* protein docking program [60], the shape of a protein molecule is represented using polar Fourier series expansions of the form

$$\sigma(\underline{x}) = \sum_{nlm} a_{nlm} R_{nl}(r) y_{lm}(\theta, \phi), \tag{1}$$

where $\sigma(\underline{x})$ is a 3D shape-density function, a_{nlm} are the expansion coefficients, $R_{nl}(r)$ are orthonormal Gauss-Laguerre polynomials and $y_{lm}(\theta, \phi)$ are the real spherical harmonics. The electrostatic potential, $\phi(\underline{x})$, and charge density, $\rho(\underline{x})$, of a protein may be represented using similar expansions. Such representations allow the *in vacuo* electrostatic interaction energy between two proteins, A and B, to be calculated as [47]

$$E = \frac{1}{2}\int \phi_A(\underline{x})\rho_B(\underline{x})\mathrm{d}\underline{x} + \frac{1}{2}\int \phi_B(\underline{x})\rho_A(\underline{x})\mathrm{d}\underline{x}. \tag{2}$$

This equation demonstrates using the notion of *overlap* between 3D scalar quantities to give a physics-based scoring function. If the aim is to find the configuration that gives the most favourable interaction energy, then it is necessary to perform a six-dimensional search in the space of available rotational and translational degrees of freedom. By re-writing the polar Fourier expansions using complex spherical harmonics, we showed previously that fast Fourier transform (FFT) techniques may be used to accelerate the search in up to five of the six degrees of freedom [61]. Furthermore, we also showed that such calculations may be accelerated dramatically on modern graphics processor units [9], [6]. Consequently, we are continuing to explore new ways to exploit the polar Fourier approach.

3.2.3. Assembling Symmetrical Protein Complexes

Although protein-protein docking algorithms are improving [62], [49], it still remains challenging to produce a high resolution 3D model of a protein complex using *ab initio* techniques, mainly due to the problem of structural flexibility described above. However, with the aid of even just one simple constraint on the docking search space, the quality of docking predictions can improve dramatically [61][9]. In particular, many protein complexes involve symmetric arrangements of one or more sub-units, and the presence of symmetry may be exploited to reduce the search space considerably [32], [58], [65]. For example, using our operator notation (in which $\widehat{R}$ and $\widehat{T}$ represent 3D rotation and translation operators, respectively), we have developed an algorithm which can generate and score candidate docking orientations for monomers that assemble into cyclic (C_n) multimers using 3D integrals of the form

$$E_{AB}(y,\alpha,\beta,\gamma) = \int \left[\widehat{T}(0,y,0)\widehat{R}(\alpha,\beta,\gamma)\phi_A(\underline{x})\right] \times \left[\widehat{R}(0,0,\omega_n)\widehat{T}(0,y,0)\widehat{R}(\alpha,\beta,\gamma)\rho_B(\underline{x})\right] \mathrm{d}\underline{x}, \tag{3}$$

where the identical monomers A and B are initially placed at the origin, and $\omega_n = 2\pi/n$ is the rotation about the principal n-fold symmetry axis. This example shows that complexes with cyclic symmetry have just 4 rigid body degrees of freedom (DOFs), compared to $6(n-1)$ DOFs for non-symmetrical n-mers. We have generalised these ideas in order to model protein complexes that crystallise into any of the naturally occurring point group symmetries (C_n, D_n, T, O, I). This approach was published in 2016 [19], and was subsequently applied to several symmetrical complexes from the “CAPRI” blind docking experiment [13]. Although we currently use shape-based FFT correlations, the symmetry operator technique may equally be used to refine candidate solutions using a more accurate coarse-grained (CG) force-field scoring function.

3.2.4. Coarse-Grained Models

Many approaches have been proposed in the literature to take into account protein flexibility during docking. The most thorough methods rely on expensive atomistic simulations using MD. However, much of a MD trajectory is unlikely to be relevant to a docking encounter unless it is constrained to explore a putative protein-protein interface. Consequently, MD is normally only used to refine a small number of candidate rigid body docking poses. A much faster, but more approximate method is to use CG normal mode analysis (NMA) techniques to reduce the number of flexible degrees of freedom to just one or a handful of the most significant vibrational modes [54], [37], [51], [52]. In our experience, docking ensembles of NMA conformations does not give much improvement over basic FFT-based soft docking [68], and it is very computationally expensive to use side-chain repacking to refine candidate soft docking poses [2].

In the last few years, CG *force-field* models have become increasingly popular in the MD community because they allow very large biomolecular systems to be simulated using conventional MD programs [31]. Typically, a CG force-field representation replaces the atoms in each amino acid with from 2 to 4 "pseudo-atoms", and it assigns each pseudo-atom a small number of parameters to represent its chemo-physical properties. By directly attacking the quadratic nature of pair-wise energy functions, coarse-graining can speed up MD simulations by up to three orders of magnitude. Nonetheless, such CG models can still produce useful models of very large multi-component assemblies [64]. Furthermore, this kind of coarse-graining effectively integrates out many of the internal DOFs to leave a smoother but still physically realistic energy surface [46]. We are therefore developing a "coarse-grained" scoring function for fast protein-protein docking and multi-component assembly in the frame of the PhD project of Maria-Elisa Ruiz-Echartea (commenced November 2016).

3.2.5. Assembling Multi-Component Complexes and Integrative Structure Modeling

We also want to develop related approaches for integrative structure modeling using cryo-electron microscopy (cryo-EM). Thanks to recently developments in cryo-EM instruments and technologies, its is now feasible to capture low resolution images of very large macromolecular machines. However, while such developments offer the intriguing prospect of being able to trap biological systems in unprecedented levels of detail, there will also come an increasing need to analyse, annotate, and interpret the enormous volumes of data that will soon flow from the latest instruments. In particular, a new challenge that is emerging is how to fit previously solved high resolution protein structures into low resolution cryo-EM density maps. However, the problem here is that large molecular machines will have multiple sub-components, some of which will be unknown, and many of which will fit each part of the map almost equally well. Thus, the general problem of building high resolution 3D models from cryo-EM data is like building a complex 3D jigsaw puzzle in which several pieces may be unknown or missing, and none of which will fit perfectly. Although we do not have precise road-map to a solution for the multi-component assembly problem, we wish to proceed firstly by putting more emphasis on the single-body terms in the scoring function, and secondly by using fast CG representations and knowledge-based distance restraints to prune large regions of the search space.

4. Application Domains

4.1. Biomedical Knowledge Discovery

Participants: Marie-Dominique Devignes [contact person], Sabeur Aridhi, David Ritchie.

This projects in this domain are carried out in collaboration with the Orpailleur Team.

Huge and ever increasing amounts of biomedical data ("Big Data") are bringing new challenges and novel opportunities for knowledge discovery in biomedicine. We are actively collaborating with biologists and clinicians to design and implement approaches for selecting, integrating, and mining biomedical data in various areas. In particular, we are focusing on leveraging bio-ontologies at all steps of this process (the main thesis topic of Gabin Personeni, co-supervised by Marie-Dominique Devignes and Adrien Coulet from the Orpailleur team). One specific application concerns exploiting Linked Open Data (LOD) to characterise the genes responsible for intellectual deficiency. This work is in collaboration with Pr. P. Jonveaux of the Laboratoire de Génétique Humaine at CHRU Nancy [56], [57]. This involves using inductive logic programming as a machine learning method and at least three different ontologies (Gene Ontology, Human Phenotype Ontology, and Disease Ontology).

Recently, a new application for biomedical knowledge discovery has emerged from the ANR "FIGHT-HF" (fight heart failure) project, which is in collaboration with several INSERM teams at CHRU Nancy. In this case, the molecular mechanisms that underly HF at the cellular and tissue levels will be considered against a background of all available data and ontologies, and represented in a single integrated complex network. A network platform is under construction with the help of a young start-up company called Edgeleap. Together with this company, we are developing query and analysis facilities to help biologists and clinicians to identify relevant biomarkers for patient phenotyping [25]. Docking of small molecules on candidate receptors, as well as protein-protein docking will also be used to clarify a certain number of relations in the complex HF network.

4.2. Prokaryotic Type IV Secretion Systems

Participants: Marie-Dominique Devignes [contact person], Bernard Maigret, Isaure Chauvot de Beauchêne, David Ritchie.

Prokaryotic type IV secretion systems constitute a fascinating example of a family of nanomachines capable of translocating DNA and protein molecules through the cell membrane from one cell to another [30]. The complete system involves at least 12 proteins. The structure of the core channel involving three of these proteins has recently been determined by cryo-EM experiments [41], [63]. However, the detailed nature of the interactions between the remaining components and those of the core channel remains to be resolved. Therefore, these secretion systems represent another family of complex biological systems (scales 2 and 3) that call for integrated modeling approaches to fully understand their machinery.

In the frame of the "MBI" platform (see Section 6.8), MD Devignes is pursuing her collaboration with Nathalie Leblond of the Genome Dynamics and Microbial Adaptation (DynAMic) laboratory (UMR 1128, Université de Lorraine, INRA) on the discovery of new integrative conjugative elements (ICEs) and integrative mobilisable elements (IMEs) in prokaryotic genomes. These elements use Type IV secretion systems for transferring DNA horizontally from one cell to another. We have discovered more than 200 new ICEs/IMEs by systematic exploration of 72 Streptococcus genome. As these elements encode all or a subset of the components of the Type IV secretion system, they constitute a valuable source of sequence data and constraints for modeling these systems in 3D. Another interesting aspect of this particular system is that unlike other secretion systems, the Type IV secretion systems are not restricted to a particular group of bacteria.

4.3. G-protein Coupled Receptors

Participants: Bernard Maigret [contact person], David Ritchie, Vincent Leroux.

G-protein coupled receptors (GPCRs) are cell surface proteins which detect chemical signals outside a cell and which transform these signals into a cascade of cellular changes. Historically, the most well documented signaling cascade is the one driven by G-proteins trimers (guanine nucleotide binding proteins) [43] which ultimately regulate many cellular processes such as transcription, enzyme activity, and homeostatis, for example. But other pathways have recently been associated with the signals triggered by GPCRs, involving other proteins such as arrestins and kinases which drive other important cellular activities. For example, β-arrestin activation can block GPCR-mediated apoptosis (cell death). Malfunctions in such processes are related to diseases such as diabetes, neurological disorders, cardiovascular disease, and cancer. Thus, GPCRs are one of the main protein families targeted by therapeutic drugs [38] and the focus of much bio-medical research. Indeed, approximately 40–50% of current therapeutic molecules target GPCRs. However, despite enormous efforts, the main difficulty here is the lack of experimentally solved 3D structures for most GPCRs. Hence, computational modeling tools are widely recognized as necessary to help understand GPCR functioning and thus biomedical innovation and drug design.

In collaboration with the BIOS team (INRA Tours) and the AMIB team (Inria Saclay – Île de France) we used our Hex protein docking software to help model a multi-component G-protein coupled receptor (GPCR) complex [35]. The resulting 3D structure was shown to be consistent with the known experimental data for the protein components of this trans-membrane molecular signaling system. As part of an on-going collaboration with the Centre for Interdisciplinary Research (CIRB) at Collège de France, we modeled the interaction between the Apelin peptide and a GPCR called ApelinR [42]. This study provided mechanistic insights which could lead to the development of therapeutic agents for the treatment of heart failure.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Awards

A figure from our article in the *Journal of Applied Crystallography* [19] was used to illustrate the front cover of the February issue of the journal.

6. New Software and Platforms

6.1. Hex

KEYWORDS: 3D rendering - Bioinformatics - 3D interaction - Structural Biology
SCIENTIFIC DESCRIPTION The underlying algorithm uses a novel polar Fourier correlation technique to accelerate the search for close-fitting orientations of the two molecules.
FUNCTIONAL DESCRIPTION Hex is an interactive protein docking and molecular superposition program. Hex understands protein and DNA structures in PDB format, and it can also read small-molecule "SDF" files. Hex will run on most Windows-XP, Linux and Mac OS X PCs. The recent versions now include CUDA support for Nvidia GPUs. On a modern workstation, docking times range from a few minutes or less when the search is constrained to known binding sites, to about half an hour for a blind global search (or just a few seconds with CUDA). On multi-processor Linux systems, docking calculation times can be reduced in almost direct proportion to the number of CPUs and GPUs used. The calculations can be accelerated by using an optional disc cache (strongly recommended) of about 1 GB of disc space.

- Participant: David Ritchie
- Contact: David Ritchie
- URL: http://hex.loria.fr

6.2. Kbdock

FUNCTIONAL DESCRIPTION Database 3D protein domain-domain interactions with a web interface

- Authors: Anisah Ghoorah, Anisah Ghoorah, David Ritchie and Marie Dominique Devignes
- Contact: David Ritchie
- URL: http://kbdock.loria.fr

6.3. Kpax

KEYWORDS: Bioinformatics - Structural Biology
SCIENTIFIC DESCRIPTION To align and superpose the 3D structures of protein molecules.

- Participant: David Ritchie
- Contact: David Ritchie
- URL: http://kbdock.loria.fr

6.4. Sam

Symmetry Assembler
FUNCTIONAL DESCRIPTION To predict the three-dimentional structures of symmetrical protein complexes using spherical polar Fourier representations

- Authors: David Ritchie and Sergey Grudinin
- Partner: CNRS
- Contact: David Ritchie
- URL: http://sam.loria.fr

6.5. ECDomainMiner

KEYWORDS: Protein Domain Annotation

SCIENTIFIC DESCRIPTION

EC-DomainMiner is a recommender-based approach for associating EC (Enzyme Commission) numbers with Pfam domains.

FUNCTIONAL DESCRIPTION

EC-DomainMiner uses a statistical recommender-based approach to infer EC-Pfam relationships from EC-sequence relationships that have been annotated previously in the SIFTS and Uniprot databases.

- Contact: David Ritchie
- URL: http://ecdm.loria.fr

6.6. Platforms

6.6.1. The MBI Platform

The MBI (Modeling Biomolecular Interactions) platform (http://bioinfo.loria.fr) was established to support collaborations between Inria Nancy – Grand Est and other research teams associated with the University of Lorraine. The platform is a research node of the Institut Français de Bioinformatique (IFB), which is the French national network of bioinformatics platforms (http://www.france-bioinformatique.fr).

- Contact: Marie-Dominique Devignes

7. New Results

7.1. Correlating Adverse Drug Side Effects

It is well known that many therapeutic drug molecules can have adverse side effects. However, when patients take several combinations of drugs it can be difficult to determine which drug is responsible for which side effect. In collaboration with Prof. Michel Dumontier of the Biomedical Informatics Research Laboratory, Stanford, we developed an approach which combines multiple ontologies such as the Anatomical Therapeutical Classification of Drugs, the ICD-9 classification of diseases, and the SNOMED-CT medical vocabulary together with the use of Pattern Structures (an extension of Formal Concept Analysis) in order to extract association rules to analyse the co-occurrence of adverse drug effects in patient records [26], [27]. A paper describing this work has been submitted to the Journal of Biomedical Semantics.

7.2. Docking Symmetrical Protein Structures

Many proteins form symmetrical complexes in which each structure contains two or more identical copies of the same sub-unit. We recently developed a novel polar Fourier docking algorithm called “Sam” for automatically assembling symmetrical protein complexes. A journal article describing the Sam algorithm has been published [19]. An article describing the results obtained when using Sam to dock several symmetrical protein complexes from the “CAPRI” docking experiment has also been published [13].

7.3. Multiple Flexible Protein Structure Alignments

Comparing two or more proteins by optimally aligning and superposing their backbone structures provides a way to detect evolutionary relationships between proteins that cannot be detected by comparing only their primary amino-acid sequences. We have recently extended our “Kpax” protein structure alignment algorithm to flexibly align pairs of structures that cannot be completely superposed by a single rigid-body transformation, and to calculate multiple alignments of several similar structures flexibly. A journal article describing the approach has been published [20].

7.4. Annotating 3D Protein Domains

Many protein chains in the Protein Data Bank (PDB) are cross-referenced with EC numbers and Pfam domains. However, these annotations do not explicitly indicate any relation between EC numbers and Pfam domains. In order to address this limitation, we developed EC-DomainMiner, a recommender-based approach for associating EC (Enzyme Commission) numbers with Pfam domains [29]. EC-DomainMiner is able to infer automatically 20,179 associations between EC numbers and Pfam domains from existing EC-chain/Pfam-chain associations from the SIFTS database as well as EC-sequence/Pfam-sequence associations from UniProt databases. A manuscript describing this work has been provisionally accepted by the journal *BMC-Bioinformatics*.

7.5. Identifying New Anti-Fungal Agents

In this collaboration with several Brasilian laboratories (at University of Mato Grosso State, University of Maringá, Embrapa, and University of Brasilia), we identified several novel small-molecule drug leads against *Trypanosoma cruzi*, a parasite responsible for Chagas disease [21]. We also proposed several small-molecule inhibitors against *Fusarium graminearum*, a fungal threat to global wheat production [15], [12].

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. PEPS

Participants: Marie-Dominique Devignes [contact person], Bernard Maigret, David Ritchie.

The team is involved in the inter-disciplinary "MODEL-ICE" project led by Nicolas Soler (DynAMic lab, UMR 1128, INRA / Univ. Lorraine). The aim is to investigate protein-protein interactions required for initiating the transfer of an ICE (Integrated Conjugative Element) from one bacterial cell to another one.

8.2. National Initiatives

8.2.1. FEDER

8.2.1.1. LBS

Participant: Marie-Dominique Devignes [contact person].

The project "LBS" (Le Bois Santé) is a consortium funded by the European Regional Development Fund (FEDER) and the French "Fonds Unique Interministériel" (FUI). The project is coordinated by Harmonic Pharma SAS. The aim of LBS is to exploit wood products in the pharmaceutical and nutrition domains. Our contribution has been in data management and knowledge discovery for new therapeutic applications.

8.2.2. ANR

8.2.2.1. Fight-HF

Participants: Marie-Dominique Devignes [contact person], Bernard Maigret, Sabeur Aridhi, David Ritchie.

This "Investissements d'Avenirs" project aims to discover novel mechanisms for heart failure and to propose decision support for precision medicine. The project has been granted € 9M, and involves many participants from Nancy University Hospital's Federation "CARTAGE" (http://www.fhu-cartage.com/). In collaboration with the Orpailleur Team, Marie-Dominique Devignes is coordinating a work-package on network-based science and drug discovery for this project.

8.2.2.2. IFB

Participants: Marie-Dominique Devignes [contact person], Sabeur Aridhi, Isaure Chauvot de Beauchêne, David Ritchie.

The Capsid team is a research node of the IFB (Institut Français de Bioinformatique), the French national network of bioinformatics platforms (http://www.france-bioinformatique.fr). The principal aim is to make bioinformatics skills and resources more accessible to French biology laboratories.

8.2.2.3. PEPSI

Participants: David Ritchie [contact person], Marie-Dominique Devignes.

The PEPSI ("Polynomial Expansions of Protein Structures and Interactions") project is a collaboration with Sergei Grudinin at Inria Grenoble – Rône Alpes (project Nano-D) and Valentin Gordeliy at the Institut de Biologie Structurale (IBS) in Grenoble. This project funded by the ANR "Modèles Numériques" program involves developing computational protein modeling and docking techniques and using them to help solve the structures of large molecular systems experimentally.

8.3. International Initiatives

8.3.1. Participation in Other International Programs

Participant: Bernard Maigret; Project: *Characterization, expression and molecular modeling of TRR1 and ALS3 proteins of Candida spp., as a strategy to obtain new drugs with action on yeasts involved in nosocomial infections;* Partner: State University of Maringá, Brasil; Funding: CNPq.

Participant: Bernard Maigret; Project: *Fusarium graminearum target selection;* Partner: Embrapa Recursos Geneticos e Biotecnologia, Brasil; Funding: CNPq.

Participant: Bernard Maigret; Project: *The thermal shock HSP90 protein as a target for new drugs against paracoccidioidomicose;* Partner: Brasília University, Brasil; Funding: CNPq.

Participant: Bernard Maigret; Project: *Protein-protein interactions for the development of new drugs;* Partner: Federal University of Goias, Brasil. Funding: Chamada MCTI/CNPq/FNDCT.

8.4. International Research Visitors

8.4.1. Visits to International Teams

8.4.1.1. Research Stays Abroad

Gabin Personeni visited the Biomedical Informatics Research Laboratory of Prof. Michel Dumontier at Stanford University for 3 months (Nov 2015 – Feb 2016).
Seyed Ziaeddin Alborzi visited the UniProt development team of Maria Martin at the European Bioinformatics Institute (EBI), Hinxton UK, for 3 months (Oct – Dec 2016) in partial fulfilment of the requirements for a European PhD.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. General Chair, Scientific Chair

Marie-Dominique Devignes is a member of the Steering Committee for the European Conference on Computational Biology (ECCB).

David Ritchie is a member of the Bureau of the GGMM (Groupe de Graphisme et Modélisation Moléculaire).

Marie-Dominique Devignes organised a workshop ("Atelier Santé") for the Fédération Charles Hermite ("Journée Enterprises", 21/01/2016).

9.1.1.2. Member of Organizing Committees

Marie-Dominique Devignes co-organised a workshop on Structural Modeling of Type IV Secretion Systems (PEPS workshop "Model-ICE", 13/12/2016).

9.1.2. Scientific Events Selection

9.1.2.1. Member of Conference Program Committees

Marie-Dominique Devignes was a member of the programme committee for KDIR-2016, ECCB-2016, and BIBM-2016.

9.1.2.2. Reviewer

David Ritchie was a reviewer for IJCAI-2016.

Marie-Dominique Devignes reviewed grant applications for the Medical Research Council (UK) and National Science Centre (Poland).

9.1.3. Journal

9.1.3.1. Member of Editorial Boards

David Ritchie is a member of the editorial board of Scientific Reports.

9.1.3.2. Reviewing Activities

The members of the team have reviewed manuscripts for *Algorithms for Molecular Biology, Bioinformatics, Current Opinion in Structural Biology, Journal of Biomedical Semantics, Journal of Computational Chemistry Journal of Chemical Information and Modeling, Journal of Molecular Recognition,* and *Proteins: Structure, Function & Bioinformatics.*

9.1.4. Invited Talks

David Ritchie gave a presentation at the *6th CAPRI Evaluation Meeting* in Tel Aviv.

9.1.5. Research Administration

Marie-Dominique Devignes is Chargée de Mission for the CyberBioHealth research axis at the LORIA and is a member of the "Comipers" recruitment committee for Inria Nancy – Grand Est.
David Ritchie is a member of the Commission de Mention Informatique (CMI) of the University of Lorraine's IAEM doctoral school, and is a member of the Bureau of the Project Committee for Inria Nancy – Grand Est.
Marie-Dominique Devignes was a member of the "Commission de spécialistes" for the recruitment of an associate professor in computer science at Telecom Nancy, Université de Lorraine, April-May 2016.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Licence: Sabeur Aridhi, *Programming Techniques and Tools,* 24 hours, L1, Telecom Nancy, Univ. Lorraine.

Licence: Sabeur Aridhi, *Big Data Hackathon,* 4 hours, L3, Telecom Nancy, Univ. Lorraine.

Licence: Marie-Dominique Devignes, *Relational Database Design and SQL,* 30 hours, L3, Telecom Nancy, Univ. Lorraine.

Master: Marie-Dominique Devignes, *Gene Discovery in Biological Databases,* 8 hours, M1, Univ. Lorraine.

9.2.2. Supervision

PhD in progress: Maria Elisa Ruiz Echartea, *Multi-component protein assembly using distance constraints,* 01/11/2016, David Ritchie.

PhD in progress: Gabin Personeni, *Exploration of linked open data in view of knowledge discovery. Application to the biomedical domain,* 01/10/2014, Marie-Dominique Devignes, Adrien Coulet.

PhD in progress: Seyed Ziaeddin Alborzi, *Large-scale exploration of 3D protein domain family binding sites,* 01/10/2014, David Ritchie, Marie-Dominique Devignes.

9.2.3. Juries

HDR: Olivier Dameron, *Ontology-based methods for analysing life science data,* Université de Rennes, 11/01/2016.

PhD: Minh-Son Phan, *Contribution á l'estimation de la similarité dans un ensemble de projections tomographiques non-orientées,* Université de Strasbourg, 07/10/2016, Pr Mohamed Tajine, Dr Étienne Baudrier, Dr Loïc Mazo.

PhD: Yassine Ghouzam, *Nouvelles approches pour l'analyse et la prédiction de la structure tridimensionnelle des protéines,* Université Paris 7, 18/10/2016, Dr Jean-Christophe Gelly.

PhD: Benoît Henry, *Probability theory applied to evolutionary biology,* Université de Lorraine, 17/11/2016, Dr Nicolas Champagnat, Dr David Ritchie.

PhD: Yoann Dufresne, *Algorithmique pour l'annotation automatique de peptides non ribosomiques,* Université de Lille, 01/12/2016, Pr Maude Pupin, Dr Laurent Noé.

9.3. Popularization

An article on our KBDOCK resource for studying protein-protein interactions was published in ERCIM News (edition 104, January 2016) [22].

The team made a presentation at the public “Cité Forum” in Nancy (01-02 Apr 2016).

10. Bibliography

Major publications by the team in recent years

[1] A. W. GHOORAH, M.-D. DEVIGNES, M. SMAÏL-TABBONE, D. RITCHIE.*Spatial clustering of protein binding sites for template based protein docking*, in "Bioinformatics", August 2011, vol. 27, n° 20, p. 2820-2827 [*DOI :* 10.1093/BIOINFORMATICS/BTR493], https://hal.inria.fr/inria-00617921.

[2] A. W. GHOORAH, M.-D. DEVIGNES, M. SMAÏL-TABBONE, D. RITCHIE.*Protein Docking Using Case-Based Reasoning*, in "Proteins", October 2013, vol. 81, n° 12, p. 2150-2158 [*DOI :* 10.1002/PROT.24433], https://hal.inria.fr/hal-00880341.

[3] A. W. GHOORAH, M.-D. DEVIGNES, M. SMAÏL-TABBONE, D. RITCHIE.*KBDOCK 2013: A spatial classification of 3D protein domain family interactions*, in "Nucleic Acids Research", January 2014, vol. 42, n° D1, p. 389-395, https://hal.inria.fr/hal-00920612.

[4] T. V. HOANG, X. CAVIN, D. RITCHIE.*gEMfitter: A highly parallel FFT-based 3D density fitting tool with GPU texture memory acceleration*, in "Journal of Structural Biology", September 2013 [*DOI :* 10.1016/J.JSB.2013.09.010], https://hal.inria.fr/hal-00866871.

[5] T. HOANG, X. CAVIN, P. SCHULTZ, D. RITCHIE.*gEMpicker: a highly parallel GPU-accelerated particle picking tool for cryo-electron microscopy*, in "BMC Structural Biology", 2013, vol. 13, n° 1, 25 [*DOI :* 10.1186/1472-6807-13-25], https://hal.inria.fr/hal-00955580.

[6] G. MACINDOE, L. MAVRIDIS, V. VENKATRAMAN, M.-D. DEVIGNES, D. RITCHIE.*HexServer: an FFT-based protein docking server powered by graphics processors*, in "Nucleic Acids Research", May 2010, vol. 38, p. W445-W449 [*DOI :* 10.1093/NAR/GKQ311], https://hal.inria.fr/inria-00522712.

[7] V. PÉREZ-NUENO, A. S. KARABOGA, M. SOUCHET, D. RITCHIE.*GESSE: Predicting Drug Side Effects from Drug–Target Relationships*, in "Journal of Chemical Information and Modeling", August 2015, vol. 55, n^o 9, p. 1804-1823 [*DOI :* 10.1021/ACS.JCIM.5B00120], https://hal.inria.fr/hal-01216493.

[8] D. RITCHIE.*Calculating and scoring high quality multiple flexible protein structure alignments*, in "Bioinformatics", May 2016, vol. 32, n^o 17, p. 2650-2658 [*DOI :* 10.1093/BIOINFORMATICS/BTW300], https://hal.inria.fr/hal-01371083.

[9] D. W. RITCHIE, V. VENKATRAMAN.*Ultra-fast FFT protein docking on graphics processors*, in "Bioinformatics", August 2010, vol. 26, n^o 19, p. 2398-2405 [*DOI :* 10.1093/BIOINFORMATICS/BTQ444], https://hal.inria.fr/inria-00537988.

[10] V. VENKATRAMAN, D. W. RITCHIE.*Predicting Multi-component Protein Assemblies Using an Ant Colony Approach*, in "International Journal of Swarm Intelligence Research", September 2012, vol. 3, p. 19-31 [*DOI :* 10.4018/JSIR.2012070102], https://hal.inria.fr/hal-00756807.

Publications of the year

Articles in International Peer-Reviewed Journal

[11] C. AMBROSET, C. COLUZZI, G. GUÉDON, M.-D. DEVIGNES, V. LOUX, T. LACROIX, S. PAYOT, N. LEBLOND-BOURGET.*New Insights into the Classification and Integration Specificity of Streptococcus Integrative Conjugative Elements through Extensive Genome Exploration*, in "Frontiers in microbiology", January 2016, vol. 6, 1483 [*DOI :* 10.3389/FMICB.2015.01483], https://hal.archives-ouvertes.fr/hal-01262284.

[12] E. BRESSO, V. LEROUX, M. URBAN, K. E. HAMMOND-KOSACK, B. MAIGRET, N. F. MARTINS.*Structure-based virtual screening of hypothetical inhibitors of the enzyme longiborneol synthase—a potential target to reduce Fusarium head blight disease*, in "Journal of Molecular Modeling", July 2016, vol. 22, n^o 7 [*DOI :* 10.1007/S00894-016-3021-1], https://hal.inria.fr/hal-01392851.

[13] M. EL HOUASLI, B. MAIGRET, M.-D. DEVIGNES, A. W. GHOORAH, S. GRUDININ, D. RITCHIE.*Modeling and minimizing CAPRI round 30 symmetrical protein complexes from CASP-11 structural models*, in "Proteins: Structure, Function, and Genetics", October 2016 [*DOI :* 10.1002/PROT.25182], https://hal.inria.fr/hal-01388654.

[14] M. F. LENSINK, S. VELANKAR, A. KRYSHTAFOVYCH, S.-Y. HUANG, D. SCHNEIDMAN-DUHOVY, A. SALI, J. SEGURA, N. FERNANDEZ-FUENTES, S. VISWANATH, R. ELBER, S. GRUDININ, P. POPOV, E. NEVEU, H. LEE, M. BAEK, S. PARK, L. HEO, G. R. LEE, C. SEOK, S. QIN, H.-X. ZHOU, D. W. RITCHIE, B. MAIGRET, M.-D. DEVIGNES, A. GHOORAH, M. TORCHALA, R. A.G. CHALEIL, P. A. BATES, E. BEN-ZEEV, M. EISENSTEIN, S. NEGI S., T. VREVEN, B. G. PIERCE, T. M. BORRMAN, J. YU, F. OCHSENBEIN, Z. WENG, R. GUEROIS, A. VANGONE, J. P. RODRIGUES, G. VAN ZUNDERT, M. NELLEN, L. XUE, E. KARACA, A. S. J. MELQUIOND, K. VISSCHER, P. L. KASTRITIS, A. M. J. J. BONVIN, X. XU, L. QIU, C. YAN, J. LI, Z. MA, J. CHENG, X. ZOU, Y. SHENG, L. X. PETERSON, H.-R. KIM, A. ROY, X. HAN, J. ESQUIVEL-RODRÍGUEZ, D. KIHARA, X. YU, N. J. BRUCE, J. C. FULLER, R. C. WADE, I. ANISHCHENKO, P. J. KUNDROTAS, I. A. VAKSER, K. IMAI, K. YAMADA, T. ODA, T. NAKAMURA,

K. TOMII, C. PALLARA, M. ROMERO-DURANA, B. JIMÉNEZ-GARCÍA, I. H. MOAL, J. FERNÁNDEZ-RECIO, J. Y. JOUNG, J. Y. KIM, K. JOO, J. LEE, D. KOZAKOV, S. VAJDA, S. MOTTARELLA, D. R. HALL, D. BEGLOV, A. MAMONOV, B. XIA, T. BOHNUUD, C. A. DEL CARPIO, E. ICHIISHI, N. MARZE, D. KURODA, S. S. R. BURMAN, J. J. GRAY, E. CHERMAK, L. CAVALLO, R. OLIVA, A. TOVCHIGRECHKO, S. J. WODAK.*Prediction of homo- and hetero-protein complexes by protein docking and template-based modeling: a CASP-CAPRI experiment*, in "Proteins - Structure, Function and Bioinformatics", February 2016 [*DOI :* 10.1002/PROT.25007], https://hal.inria.fr/hal-01309105.

[15] M. MARTINS, E. BRESSO, R. C. TOGAWA, M. URBAN, J. ANTONIW, B. MAIGRET, K. HAMMOND-KOSACK.*Searching for Novel Targets to Control Wheat Head Blight Disease—I-Protein Identification, 3D Modeling and Virtual Screening*, in "Advances in Microbiology", September 2016, vol. 06, n^{o} 11, p. 811 - 830 [*DOI :* 10.4236/AIM.2016.611079], https://hal.inria.fr/hal-01392860.

[16] E. NEVEU, D. RITCHIE, P. POPOV, S. GRUDININ.*PEPSI-Dock: a detailed data-driven protein–protein interaction potential accelerated by polar Fourier correlation*, in "Bioinformatics", September 2016 [*DOI :* 10.1093/BIOINFORMATICS/BTW443], https://hal.archives-ouvertes.fr/hal-01358645.

[17] D. PADHORNY, A. KAZENNOV, B. S. ZERBE, K. A. PORTER, B. XIA, S. MOTTARELLA, Y. KHOLODOV, D. RITCHIE, S. VAJDA, D. KOZAKOV.*Protein–protein docking by fast generalized Fourier transforms on 5D rotational manifolds*, in "PNAS Early Edition", May 2016, vol. 113, n^{o} 30, p. E4286-E4293 [*DOI :* 10.1073/PNAS.1603929113], https://hal.inria.fr/hal-01371087.

[18] M. RICHARD, A. CHATEAU, C. JELSCH, C. DIDIERJEAN, X. MANIVAL, C. CHARRON, B. MAIGRET, M. BARBERI-HEYOB, Y. CHAPLEUR, C. BOURA, N. PELLEGRINI-MOÏSE.*Carbohydrate-based peptidomimetics targeting neuropilin-1: synthesis, molecular docking study and in vitro biological activities*, in "Bioorganic and Medicinal Chemistry", November 2016, vol. 24, n^{o} 21, p. 5315-5325 [*DOI :* 10.1016/J.BMC.2016.08.052], https://hal.archives-ouvertes.fr/hal-01360034.

[19] D. W. RITCHIE, S. GRUDININ.*Spherical polar Fourier assembly of protein complexes with arbitrary point group symmetry*, in "Journal of Applied Crystallography", February 2016, vol. 49, n^{o} 1, p. 158-167 [*DOI :* 10.1107/S1600576715022931], https://hal.inria.fr/hal-01261402.

[20] D. RITCHIE.*Calculating and scoring high quality multiple flexible protein structure alignments*, in "Bioinformatics", May 2016, vol. 32, n^{o} 17, p. 2650-2658 [*DOI :* 10.1093/BIOINFORMATICS/BTW300], https://hal.inria.fr/hal-01371083.

[21] H. DE ALMEIDA, V. LEROUX, F. N. MOTTA, P. GRELLIER, B. MAIGRET, J. M. SANTANA, I. M. D. BASTOS.*Identification of novel Trypanosoma cruzi prolyl oligopeptidase inhibitors by structure-based virtual screening*, in "Journal of Computer-Aided Molecular Design", October 2016 [*DOI :* 10.1007/S10822-016-9985-1], https://hal.inria.fr/hal-01392842.

Articles in Non Peer-Reviewed Journal

[22] M.-D. DEVIGNES, M. SMAÏL-TABBONE, D. RITCHIE.*Kbdock - Searching and organising the structural space of protein-protein interactions*, in "ERCIM News", January 2016, n^{o} 104, p. 24-25, https://hal.inria.fr/hal-01258117.

International Conferences with Proceedings

[23] C. CHAMARD-JOVENIN, A. CHESNEL, E. BRESSO, C. MOREL, C. THIÉBAUT, M. SMAÏL-TABBONE, E.-H. DJERMOUNE, M.-D. DEVIGNES, T. BOUKHOBZA, H. DUMOND.*Transgenerational effects of ERalpha36 over-expression on mammary gland development and molecular phenotype: clinical perspective for breast cancer risk and therapy*, in "21st World Congress on Advances in Oncology and 19th International Symposium on Molecular Medicine", Athens, Greece, October 2016, https://hal.archives-ouvertes.fr/hal-01416469.

[24] C. CHAMARD-JOVENIN, A. CHESNEL, C. MOREL, M.-D. DEVIGNES, M. SMAÏL-TABBONE, T. BOUKHOBZA, H. DUMOND.*Long chain alkylphenol mixture promotes breast cancer initiation and progression through an ERα36-mediated mechanism*, in "2nd French Workshop on Endocrine disruption in wildlife and human health", Paris, France, January 2016, Présentation Poster, https://hal.archives-ouvertes.fr/hal-01320688.

[25] K. DALLEAU, M. COUCEIRO, M.-D. DEVIGNES, C. RAÏSSI, M. SMAÏL-TABBONE.*Using aggregation functions on structured data: a use case in the FIGHT-HF project*, in "International Symposium on Aggregation and Structures (ISAS 2016)", Luxembourg, Luxembourg, G. KISS, J.-L. MARICHAL, B. TEHEUX (editors), International Symposium on Aggregation and Structures (ISAS 2016) - Book of abstracts, July 2016, https://hal.inria.fr/hal-01399232.

National Conferences with Proceeding

[26] G. PERSONENI, M.-D. DEVIGNES, M. DUMONTIER, M. SMAÏL-TABBONE, A. COULET.*Extraction d'association d'EIM à partir de dossiers patients : expérimentation avec les structures de patrons et les ontologies*, in "Deuxième Atelier sur l'Intelligence Artificielle et la Santé", Montpellier, France, Atelier IA & Santé, June 2016, https://hal.inria.fr/hal-01391172.

Conferences without Proceedings

[27] G. PERSONENI, M.-D. DEVIGNES, M. DUMONTIER, M. SMAÏL-TABBONE, A. COULET.*Discovering ADE associations from EHRs using pattern structures and ontologies*, in "Phenotype Day, Bio-Ontologies SIG, ISMB", Orlando, United States, July 2016, https://hal.inria.fr/hal-01369448.

Scientific Books (or Scientific Book chapters)

[28] A. W. GHOORAH, M.-D. DEVIGNES, M. SMAÏL-TABBONE, D. RITCHIE.*Classification and Exploration of 3D Protein Domain Interactions Using Kbdock*, in "Data Mining Techniques for the Life Sciences", O. CARUGO, F. EISENHABER (editors), Methods in Molecular Biology, Springer Science+Business Media New York, 2016, vol. 1415, p. 91-105 [*DOI :* 10.1007/978-1-4939-3572-7_5], https://hal.inria.fr/hal-01317448.

References in notes

[29] S. Z. ALBORZI, M.-D. DEVIGNES, D. RITCHIE.*EC-PSI: Associating Enzyme Commission Numbers with Pfam Domains*, in "JOBIM 2015", Clermont-Ferrand, France, July 2015 [*DOI :* 10.1101/022343], https://hal.inria.fr/hal-01216743.

[30] C. E. ALVAREZ-MARTINEZ, P. J. CHRISTIE.*Biological diversity of prokaryotic type IV secretion systems*, in "Microbiology and Molecular Biology Reviews", 2011, vol. 73, p. 775–808.

[31] M. BAADEN, S. R. MARRINK.*Coarse-grained modelling of protein-protein interactions*, in "Current Opinion in Structural Biology", 2013, vol. 23, p. 878–886.

[32] A. BERCHANSKI, M. EISENSTEIN.*Construction of molecular assemblies via docking: modeling of tetramers with D_2 symmetry*, in "Proteins", 2003, vol. 53, p. 817–829.

[33] H. M. BERMAN, T. BATTISTUZ, T. N. BHAT, W. F. BLUHM, P. E. BOURNE, K. BURKHARDT, Z. FENG, G. L. GILLILAND, L. IYPE, S. JAIN, P. FAGAN, J. MARVIN, D. PADILLA, V. RAVICHANDRAN, B. SCHNEIDER, N. THANKI, H. WEISSIG, J. D. WESTBROOK, C. ZARDECKI.*The Protein Data Bank*, in "Acta. Cryst.", 2002, vol. D58, p. 899–907.

[34] P. BORK, L. J. JENSEN, C. VON MERING, A. K. RAMANI, I. LEE, E. M. MARCOTTE.*Protein interaction networks from yeast to human*, in "Current Opinion in Structural Biology", 2004, vol. 14, p. 292–299.

[35] T. BOURQUARD, F. LANDOMIEL, E. REITER, P. CRÉPIEUX, D. W. RITCHIE, J. AZÉ, A. POUPON.*Unraveling the molecular architecture of a G protein-coupled receptor/β-arrestin/Erk module complex*, in "Scientific Reports", June 2015, 5:10760 [*DOI :* 10.1038/SREP10760], http://hal-lirmm.ccsd.cnrs.fr/lirmm-01162594.

[36] M.-D. DEVIGNES, B. SIDAHMED, M. SMAÏL-TABBONE, N. AMEDEO, P. OLIVIER.*Functional classification of genes using semantic distance and fuzzy clustering approach: Evaluation with reference sets and overlap analysis*, in "international Journal of Computational Biology and Drug Design. Special Issue on: ”Systems Biology Approaches in Biological and Biomedical Research”", 2012, vol. 5, n^{o} 3/4, p. 245-260, https://hal.inria.fr/hal-00734329.

[37] S. E. DOBBINS, V. I. LESK, M. J. E. STERNBERG.*Insights into protein flexibility: The relationship between normal modes and conformational change upon protein–protein docking*, in "Proceedings of National Academiy of Sciences", 2008, vol. 105, n^{o} 30, p. 10390–10395.

[38] D. FILMORE.*It's a GPCR world*, in "Modern Drug Discovery", 2004, vol. 7, p. 24–28.

[39] R. D. FINN, J. MISTRY, J. TATE, P. COGGILL, A. HEGER, J. E. POLLINGTON, O. L. GAVIN, P. GUNASEKARAN, G. CERIC, K. FORSLUND, L. HOLM, E. L. L. SONNHAMMER, S. R. EDDY, A. BATEMAN.*The Pfam protein families database*, in "Nucleic Acids Research", 2010, vol. 38, p. D211–D222.

[40] W. J. FRAWLEY, G. PIATETSKY-SHAPIRO, C. J. MATHEUS.*Knowledge Discovery in Databases: An Overview*, in "AI Magazine", 1992, vol. 13, p. 57–70.

[41] R. FRONZES, E. SCHÄFER, L. WANG, H. R. SAIBIL, E. V. ORLOVA, G. WAKSMAN.*Structure of a type IV secretion system core complex*, in "Science", 2011, vol. 323, p. 266–268.

[42] R. GERBIER, V. LEROUX, P. COUVINEAU, R. ALVEAR-PEREZ, B. MAIGRET, C. LLORENS-CORTES, X. ITURRIOZ.*New structural insights into the apelin receptor: identification of key residues for apelin binding*, in "FASEB Journal", January 2015, vol. 29, n^{o} 1, p. 314-322 [*DOI :* 10.1096/FJ.14-256339], https://hal.inria.fr/hal-01251633.

[43] A. G. GILMAN.*G proteins: transducers of receptor-generated signaling*, in "Annual Review of Biochemistry", 1987, vol. 56, p. 615–649.

[44] R. A. GOLDSTEIN.*The structure of protein evolution and the evolution of proteins structure*, in "Current Opinion in Structural Biology", 2008, vol. 18, p. 170–177.

[45] H. HERMJAKOB, L. MONTECCHI-PALAZZI, G. BADER, J. WOJCIK, L. SALWINSKI, A. CEOL, S. MOORE, S. ORCHARD, U. SARKANS, C. VON MERING, B. ROECHERT, S. POUX, E. JUNG, H. MERSCH, P. KERSEY, M. LAPPE, Y. LI, R. ZENG, D. RANA, M. NIKOLSKI, H. HUSI, C. BRUN, K. SHANKER, S. G. N. GRANT, C. SANDER, P. BORK, W. ZHU, A. PANDEY, A. BRAZMA, B. JACQ, M. VIDAL, D. SHERMAN, P. LEGRAIN, G. CESARENI, I. XENARIOS, D. EISENBERG, B. STEIPE, C. HOGUE, R. APWEILER.*The HUPO PSI's Molecular Interaction format – a community standard for the representation of protein interaction data*, in "Nature Biotechnology", 2004, vol. 22, n° 2, p. 177-183.

[46] H. I. INGÓLFSSON, C. A. LOPEZ, J. J. UUSITALO, D. H. DE JONG, S. M. GOPAL, X. PERIOLE, S. R. MARRINK.*The power of coarse graining in biomolecular simulations*, in "WIRES Comput. Mol. Sci.", 2013, vol. 4, p. 225–248, http://dx.doi.org/10.1002/wcms.1169.

[47] J. D. JACKSON.*Classical Electrodynamics*, Wiley, New York, 1975.

[48] P. J. KUNDROTAS, Z. W. ZHU, I. A. VAKSER.*GWIDD: Genome-wide protein docking database*, in "Nucleic Acids Research", 2010, vol. 38, p. D513–D517.

[49] M. F. LENSINK, S. J. WODAK.*Docking and scoring protein interactions: CAPRI 2009*, in "Proteins", 2010, vol. 78, p. 3073–3084.

[50] L. MAVRIDIS, V. VENKATRAMAN, D. W. RITCHIE.*A Comprehensive Comparison of Protein Structural Alignment Algorithms*, in "3DSIG – 8th Structural Bioinformatics and Computational Biophysics Meeting", Long Beach, California, ISMB, 2012, vol. 8, 89.

[51] A. MAY, M. ZACHARIAS.*Energy minimization in low-frequency normal modes to efficiently allow for global flexibility during systematic protein-protein docking*, in "Proteins", 2008, vol. 70, p. 794–809.

[52] I. H. MOAL, P. A. BATES.*SwarmDock and the Use of Normal Modes in Protein-Protein Docking*, in "International Journal of Molecular Sciences", 2010, vol. 11, n° 10, p. 3623–3648.

[53] C. MORRIS.*Towards a structural biology work bench*, in "Acta Crystallographica", 2013, vol. PD69, p. 681–682.

[54] D. MUSTARD, D. RITCHIE.*Docking essential dynamics eigenstructures*, in "Proteins: Structure, Function, and Genetics", 2005, vol. 60, p. 269-274 [*DOI :* 10.1002/PROT.20569], https://hal.inria.fr/inria-00434271.

[55] S. ORCHARD, S. KERRIEN, S. ABBANI, B. ARANDA, J. BHATE, S. BIDWELL, A. BRIDGE, L. BRIGANTI, F. S. L. BRINKMAN, G. CESARENI, A. CHATRARYAMONTRI, E. CHAUTARD, C. CHEN, M. DUMOUSSEAU, J. GOLL, R. E. W. HANCOCK, L. I. HANNICK, I. JURISICA, J. KHADAKE, D. J. LYNN, U. MAHADEVAN, L. PERFETTO, A. RAGHUNATH, S. RICARD-BLUM, B. ROECHERT, L. SALWINSKI, V. STÜMPFLEN, M. TYERS, P. UETZ, I. XENARIOS, H. HERMJAKOB.*Protein interaction data curation: the International Molecular Exchange (IMEx) consortium*, in "Nature Methods", 2012, vol. 9, n° 4, p. 345-350.

[56] G. PERSONENI, S. DAGET, C. BONNET, P. JONVEAUX, M.-D. DEVIGNES, M. SMAÏL-TABBONE, A. COULET.*ILP for Mining Linked Open Data: a biomedical Case Study*, in "The 24th International Conference on Inductive Logic Programming (ILP 2014)", Nancy, France, September 2014, https://hal.inria.fr/hal-01095597.

[57] G. PERSONENI, S. DAGET, C. BONNET, P. JONVEAUX, M.-D. DEVIGNES, M. SMAÏL-TABBONE, A. COULET.*Mining Linked Open Data: A Case Study with Genes Responsible for Intellectual Disability*, in "Data Integration in the Life Sciences - 10th International Conference, DILS 2014", Lisbon, Portugal, H. GALHARDAS, E. RAHM (editors), Lecture Notes in Computer Science, Springer, 2014, vol. 8574, p. 16 - 31, https://hal.inria.fr/hal-01095591.

[58] B. PIERCE, W. TONG, Z. WENG.*M-ZDOCK: A Grid-Based Approach for C_n Symmetric Multimer Docking*, in "Bioinformatics", 2005, vol. 21, n° 8, p. 1472–1478.

[59] D. RITCHIE, A. GHOORAH, L. MAVRIDIS, V. VENKATRAMAN.*Fast Protein Structure Alignment using Gaussian Overlap Scoring of Backbone Peptide Fragment Similarity*, in "Bioinformatics", October 2012, vol. 28, n° 24, p. 3274-3281 [*DOI :* 10.1093/BIOINFORMATICS/BTS618], https://hal.inria.fr/hal-00756813.

[60] D. RITCHIE, G. J. KEMP.*Protein docking using spherical polar Fourier correlations*, in "Proteins: Structure, Function, and Genetics", 2000, vol. 39, p. 178-194, https://hal.inria.fr/inria-00434273.

[61] D. RITCHIE, D. KOZAKOV, S. VAJDA.*Accelerating and focusing protein–protein docking correlations using multi-dimensional rotational FFT generating functions*, in "Bioinformatics", June 2008, vol. 24, n° 17, p. 1865-1873 [*DOI :* 10.1093/BIOINFORMATICS/BTN334], https://hal.inria.fr/inria-00434264.

[62] D. RITCHIE.*Recent Progress and Future Directions in Protein-Protein Docking*, in "Current Protein and Peptide Science", February 2008, vol. 9, n° 1, p. 1-15 [*DOI :* 10.2174/138920308783565741], https://hal.inria.fr/inria-00434268.

[63] A. RIVERA-CALZADA, R. FRONZES, C. G. SAVVA, V. CHANDRAN, P. W. LIAN, T. LAEREMANS, E. PARDON, J. STEYAERT, H. REMAUT, G. WAKSMAN, E. V. ORLOVA.*Structure of a bacterial type IV secretion core complex at subnanometre resolution*, in "EMBO Journal", 2013, vol. 32, p. 1195–1204.

[64] M. G. SAUNDERS, G. A. VOTH.*Coarse-grainiing of multiprotein assemblies*, in "Current Opinion in Structural Biology", 2012, vol. 22, p. 144–150.

[65] D. SCHNEIDMAN-DUHOVNY, Y. INBAR, R. NUSSINOV, H. J. WOLFSON.*Geometry-based flexible and symmetric protein docking*, in "Proteins", 2005, vol. 60, n° 2, p. 224–231.

[66] M. L. SIERK, G. J. KLEYWEGT.*Déjà vu all over again: Finding and analyzing protein structure similarities*, in "Structure", 2004, vol. 12, p. 2103–2011.

[67] S. VELANKAR, J. M. DANA, J. JACOBSEN, G. VAN GINKEL, P. J. GANE, J. LUO, T. J. OLDFIELD, C. O'DONOVAN, M.-J. MARTIN, G. J. KLEYWEGT.*SIFTS: Structure Integration with Function, Taxonomy and Sequences resource*, in "Nucleic Acids Research", 2012, vol. 41, p. D483–D489.

[68] V. VENKATRAMAN, D. RITCHIE.*Flexible protein docking refinement using pose-dependent normal mode analysis*, in "Proteins", June 2012, vol. 80, n° 9, p. 2262-2274 [*DOI :* 10.1002/PROT.24115], https://hal.inria.fr/hal-00756809.

[69] A. B. WARD, A. SALI, I. A. WILSON.*Integrative Structural Biology*, in "Biochemistry", 2013, vol. 6122, p. 913–915.

[70] S. YAND, P. E. BOURNE.*The Evolutionary History of Protein Domains Viewed by Species Phylogeny*, in "PLoS One", 2009, vol. 4, e8378.

[71] Q. C. ZHANG, D. PETREY, L. DENG, L. QIANG, Y. SHI, C. A. THU, B. BISIKIRSKA, C. LEFEBVRE, D. ACCILI, T. HUNTER, T. MANIATIS, A. CALIFANO, B. HONIG.*Structure-based prediction of protein-protein interactions on a genome-wide scale*, in "Nature", 2012, vol. 490, p. 556–560.

[72] A. ÖZGUR, Z. XIANG, D. R. RADEV, Y. HE.*Mining of vaccine-associated IFN-γ gene interaction networks using the Vaccine Ontology*, in "Journal of Biomedical Semantics", 2011, vol. 2 (Suppl 2), S8.

Project-Team CARAMBA

Cryptology, Arithmetic: Algebraic Methods for Better Algorithms

IN PARTNERSHIP WITH:
CNRS

Université de Lorraine

RESEARCH CENTER
Nancy - Grand Est

THEME
Algorithmics, Computer Algebra and Cryptology

Table of contents

Project-Team CARAMBA

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

Keywords:

Computer Science and Digital Science:

1.1.2. - Hardware accelerators (GPGPU, FPGA, etc.)
4.3.1. - Public key cryptography
4.3.2. - Secret key cryptography
4.8. - Privacy-enhancing technologies
6.2.7. - High performance computing
7.1. - Parallel and distributed algorithms
7.6. - Computer Algebra
7.7. - Number theory
7.12. - Computer arithmetic

Other Research Topics and Application Domains:

8.5. - Smart society
9.4.1. - Computer science
9.4.2. - Mathematics
9.8. - Privacy

1. Members

Research Scientists

Emmanuel Thomé [Team leader, Inria, Senior Researcher, HDR]
Jérémie Detrey [Inria, Researcher]
Pierrick Gaudry [CNRS, Senior Researcher, HDR]
Aurore Guillevic [Inria, Researcher]
Pierre-Jean Spaenlehauer [Inria, Researcher]
Paul Zimmermann [Inria, Senior Researcher, HDR]

Faculty Members

Marine Minier [Univ. Lorraine, Professor, HDR]
Marion Videau [Univ. Lorraine, Associate Professor, on leave with Quarkslab since Jan 2015]

PhD Students

Simon Abelard [Univ. Lorraine]
Svyatoslav Covanov [Univ. Lorraine]
Laurent Grémy [Univ. Lorraine]
Hugo Labrande [Univ. Lorraine, until Aug 2016]

Post-Doctoral Fellows

Enea Milio [Inria, from April 2016]
Shashank Singh [Inria, from Oct 2016]

Administrative Assistants

Virginie Priester [CNRS, from Apr 2016]
Sophie Drouot [Inria]
Laurence Félicité [Univ. Lorraine]

Others

Robin Fedele [Inria, Internship, from May 2016 until Jun 2016]
Nicolas Levy [ENS Lyon, intern, from Jun 2016 until Jul 2016]
Joshua Peignier [ENS Rennes, intern, from May 2016 until Jul 2016]
Luc Sanselme [Min. de l'Éducation Nationale, Teacher]
Élise Tasso [Univ. Lorraine, intern, from Sep 2016 until Jun 2016]

2. Overall Objectives

2.1. Overall Objectives

Our research addresses the broad application domain of cryptography and cryptanalysis from the algorithmic perspective. We study all the algorithmic aspects, from the top-level mathematical background down to the optimized high-performance software implementations. Several kinds of mathematical objects are commonly encountered in our research. Some basic ones are truly ubiquitous: integers, finite fields, polynomials, real and complex numbers. We also work with more structured objects such as number fields, algebraic curves, or polynomial systems. In all cases, our work is geared towards making computations with these objects effective and fast.

The mathematical objects we deal with are of utmost importance for the applications to cryptology, as they are the background of the most widely developed cryptographic primitives, such as the RSA cryptosystem or the Diffie–Hellman key exchange. The two facets of cryptology—cryptography and cryptanalysis—are central to our research. The key challenges are the assessment of the security of proposed cryptographic primitives, through the study of the cornerstone problems, which are the integer factorization and discrete logarithm problems, as well as the optimization work in order to enable cryptographic implementations that are both efficient *and* secure.

Among the research themes we set forth, two are guided by the most important mathematical objects used in today's cryptography, and two others are rather guided by the technological background we use to address these problems.

- Extended NFS family. A common algorithmic framework, called the Number Field Sieve (NFS), addresses both the integer factorization problem as well as the discrete logarithm problem over finite fields. We have numerous algorithmic contributions in this context, and develop software to illustrate them.

  We plan to improve on the existing state of the art in this domain by researching new algorithms, by optimizing the software performance, and by demonstrating the reach of our software with highly visible computations.
- Algebraic curves and their Jacobians. We develop algorithms and software for computing essential properties of algebraic curves for cryptology, eventually enabling their widespread cryptographic use.

  One of the challenges we address here is point counting. In a wider perspective, we also study the link between abelian varieties over finite fields and principally polarized abelian varieties over fields of characteristic zero, together with their endomorphism ring. In particular, we work in the direction of making this link an effective one. We are also investigating various approaches for attacking the discrete logarithm problem in Jacobians of algebraic curves.
- Arithmetic. Our work relies crucially on efficient arithmetic, be it for small or large sizes. We work on improving algorithms and implementations, for computations that are relevant to our application areas.
- Polynomial systems. It is rather natural with algebraic curves, and occurs also in NFS-related contexts, that many important challenges can be represented via polynomial systems, which have structural specificities. We intend to develop algorithms and tools that, when possible, take advantage of these specificities.

As represented by Figure 1, the first two challenges above interact with the latter two, which are also research topics in their own right. Both algorithmic and software improvements are the necessary ingredients for success. The different axes of our research form thus a coherent set of research directions, where we apply a common methodology.

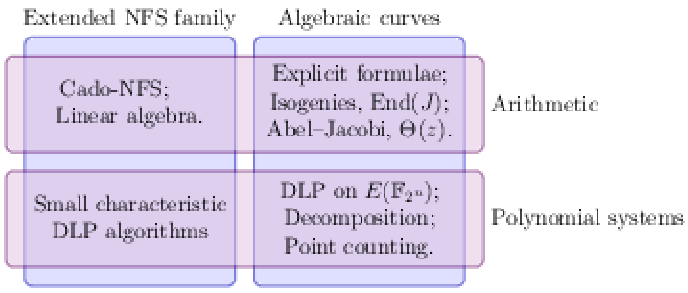

Figure 1. Visual representation of the thematic organization of CARAMBA.

We consider that the impact of our research on cryptology in general owes a lot to the publication of concrete practical results. We are strongly committed to making our algorithms available as software implementations. We thus have several long-term software development projects that are, and will remain, parts of our research activity.

2.2. Scientific Grounds

Public-key cryptography is our main application target. We are interested in the study of the cryptographic primitives that serve as a basis for the most widespread protocols.

Since the early days of public-key cryptography, and through the practices and international standards that have been established for several decades, the most widespread cryptographic primitives have been the RSA cryptosystem, as well as the Diffie–Hellman key exchange using multiplicative groups of finite fields. The level of security provided by these cryptographic primitives is related to the hardness of the underlying mathematical problems, which are integer factorization and the discrete logarithm problem. The complexity of attacking them is known to be subexponential in the public key size, and more precisely written as $L_N(1/3, c)$ for factoring an integer N, where the L notation stands for

$$L_N(\alpha, c) = \exp\left(c(1+o(1))(\log N)^{\alpha}(\log\log N)^{1-\alpha}\right).$$

This complexity is achieved with the Number Field Sieve (NFS) algorithm and its many derivatives. This means that as the desired security level s grows, the matching public key size grows roughly like s^3. As to how these complexity estimates translate into concrete assessments and recommendations, the hard facts are definitely the computational records that are set periodically by academics, and used as key ingredients by governmental agencies emitting recommendations for the industry [36], [23].

Software for NFS is obviously the entry point to computational records. Few complete NFS implementations exist, and their improvement is of crucial importance for better assessment of the hardness of the key cryptographic primitives considered. Here, “improvement” may be understood in many ways: better algorithms (outperforming the NFS algorithm as a whole is certainly a tremendous improvement, but replacing one of its numerous substeps is one, too), better implementations, better parallelization, or better adaptation to suitable hardware. The numerous sub-algorithms of NFS strongly depend on arithmetic efficiency. This concerns various mathematical objects, from integers and polynomials to ideals in number fields, lattices, or linear algebra.

Since the early 1990's, no new algorithm improved on the complexity of NFS. As it is used in practice, the algorithm has complexity $L_N(1/3, (64/9)^{1/3})$ for factoring general integers or for computing discrete logarithms in prime fields of similar size (the so-called "multiple polynomial" variants have better complexity by a very thin margin, but this has not yet yielded to a practical improvement). Given the wide use of the underlying hard problems, progress in this area is of utmost importance. In 2013, several new algorithms have modified the complexity of the discrete logarithm problem in small characteristic fields, which is a closely related problem, reaching a heuristic quasi-polynomial time algorithm [24], [31], [30], [29]. A stream of computational records have been obtained since 2013 using these algorithms, using in particular techniques from polynomial system solving, or from Galois theory. These new algorithms, together with these practical realizations, have had a very strong impact of course on the use of small-characteristic fields for cryptography (now clearly unsuitable), as well as on pairings on elliptic curves over small-characteristic finite fields (which are also no longer considered safe to use).

While it is relatively easy to set public key sizes for RSA or Diffie–Hellman that are "just above" the reach of academic computing power with NFS, the sensible cryptographic choice is to aim at security parameters that are of course well above this feasibility limit, in particular because assessing this limit precisely is in fact a very difficult problem. In line with the security levels offered by symmetric primitives such as AES-128, public key sizes should be chosen so that with current algorithmic knowledge, an attacker would need at least 2^{128} elementary operations to solve the underlying hard problem. Such security parameters would call for RSA key sizes above 3,000 bits, which is seldom seen, except in contexts where computing power is plentiful anyway.

Since the mid-1980's, elliptic curves, and more generally Jacobians of algebraic curves, have been proposed as alternative mathematical settings for building cryptographic primitives.

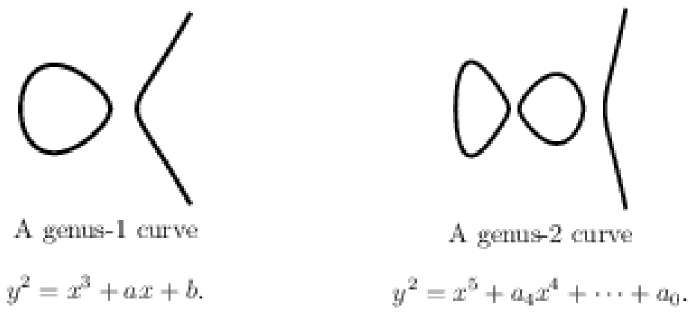

Figure 2.

The discrete logarithm problem in these groups is formidably hard, and in comparison to the situation with the traditional primitives mentioned above, the cryptanalysis algorithms are such that the appropriate public-key size grows only linearly with the desired security level: a 256-bit public key, using algebraic curves, is well suited to match the hardness of AES-128. This asset makes algebraic curves more attractive for the future of public-key cryptography.

Challenges related to algebraic curves in cryptology are rather various, and call for expertise in several areas. Suggesting curves to be used in the cryptographic context requires to solve the point counting problem. This may be done by variants of the Schoof–Elkies–Atkin algorithm and its generalizations (which, in genus 2, require arithmetic modulo multivariate systems of equations), or alternatively the use of the complex multiplication method, a rich theory that opens the way to several problems in computational number theory.

The long-awaited transition from the legacy primitives to primitives based on curves is ready to happen, only circumstantially slowed down presently by the need to agree on a new set of elliptic curves (not because of any attack, but because of skepticism over how the currently widespread ones have been generated). The Internet Research Task Force has completed in 2015 a standardization proposal [34]. In this context, the recommended curves are not of the complex multiplication family, and enjoy instead properties that allow fast implementation, and avoid a few implementation difficulties. Those are also naturally chosen to be immune to the few known attacks on the discrete logarithm problem for curves. No curve of genus 2 has made its way to the standardization process so far, however one candidate exists for the 128-bit security level [28].

The discrete logarithm problem on curves is very hard. Some results were obtained however for curves over extension fields, using techniques such as the Weil descent, or the point decomposition problem. In this context, the algorithmic setup connects to polynomial system solving, fast arithmetic, and linear algebra.

Another possible route for transitioning away from RSA and finite field-based cryptography is suggested, namely the switch to the "post-quantum" cryptographic primitives. Public-key cryptographic primitives that rely on mathematical problems related to Euclidean lattices or coding theory have an advantage: they would resist the potential advent of a quantum computer. Research on these topics is quite active, and there is no doubt that when the efficiency challenges that are currently impeding their deployment are overcome, the standardization of some post-quantum cryptographic primitives will be a worthwhile addition to the general cryptographic portfolio. The NSA has recently devoted an intriguing position text to this topic [37] (for a glimpse of some of the reactions within the academic community, the reference [33] is useful). Post-quantum cryptography, as a research topic, is complementary to the topics we address most, which are NFS and algebraic curves. We are absolutely confident that, at the very least for the next decade, primitives based on integer factoring, finite fields, and algebraic curves will continue to hold the lion's share in the cryptographic landscape. We also expect that before the advent of standardized and widely developed post-quantum cryptographic primitives, the primitives based on algebraic curves will become dominant (despite the apparent restraint from the NSA on this move).

We acknowledge that the focus on cryptographic primitives is part of a larger picture. Cryptographic primitives are part of cryptographic protocols, which eventually become part of cryptographic software. All these steps constitute research topics in their own right, and need to be scrutinized (as part of independent research efforts) in order to be considered as dependable building blocks. This being said, the interplay of the different aspects, from primitives to protocols, sometimes spawns very interesting and fruitful collaborations. A very good example of this is the LogJam attack [22].

3. Research Program

3.1. The Extended Family of the Number Field Sieve

The Number Field Sieve (NFS) has been the leading algorithm for factoring integers for more than 20 years, and its variants have been used to set records for discrete logarithms in finite fields. It is reasonable to understand NFS as a framework that can be used to solve various sorts of problems. Factoring integers and computing discrete logarithms are the most prominent for the cryptographic observer, but the same framework can also be applied to the computation of class groups.

The state of the art with NFS is built from numerous improvements of its inner steps. In terms of algorithmic improvements, the recent research activity on the NFS family has been rather intense. Several new algorithms have been discovered in over the 2014–2016 period, and their practical reach has been demonstrated by actual experiments.

The algorithmic contributions of the CARAMBA members to NFS would hardly be possible without access to a dependable software implementation. To this end, members of the CARAMBA team have been developing the Cado-NFS software suite since 2007. Cado-NFS is now the most widely visible open source implementation of NFS, and is a crucial platform for developing prototype implementations for new ideas for the many sub-algorithms of NFS. Cado-NFS is free software (LGPL) and follows an open development model, with publicly accessible development repository and regular software releases. Competing free software implementations exist, such as `msieve`, developed by J. Papadopoulos. In Lausanne, T. Kleinjung develops his own code base, which is unfortunately not public.

The workplan of CARAMBA on the topic of the Number Field Sieve algorithm and its cousins includes the following aspects:

- Pursue the work on NFS, which entails in particular making it ready to tackle larger challenges. Several of the important computational steps of NFS that are currently identified as stumbling blocks will require algorithmic advances and implementation improvements. We will illustrate the importance of this work by computational records.
- Work on the specific aspects of the computation of discrete logarithms in finite fields.
- As a side topic, the application of the broad methodology of NFS to the treatment of “ideal lattices” and their use in cryptographic proposals based on Euclidean lattices is also relevant.

3.2. Algebraic Curves in Cryptology

The challenges associated to algebraic curves in cryptology are diverse, because of the variety of mathematical objects to be considered. These challenges are also connected to each other. On the cryptographic side, efficiency matters. As of 2016, the most widely used set of elliptic curves, the so-called NIST curves, are in the process of being replaced by a new set of candidate elliptic curves for future standardization. This is the topic of RFC 7748 [34].

On the cryptanalytic side, the discrete logarithm problem on (Jacobians of) curves has resisted all attempts for many years. Among the currently active topics, the decomposition algorithms raise interesting problems related to polynomial system solving, as do attempts to solve the discrete logarithm problem on curves defined over binary fields. In particular, while it is generally accepted that the so-called Koblitz curves (base field extensions of curves defined over $\mathrm{GF}(2)$) are likely to be a weak class among the various curve choices, no concrete attack supports this claim fully.

The research objectives of CARAMBA on the topic of algebraic curves for cryptology are as follows:

- Work on the practical realization of some of the rich mathematical theory behind algebraic curves. In particular, some of the fundamental mathematical objects have potentially important connections to the broad topic of cryptology: Abel-Jacobi map, Theta functions, computation of isogenies, computation of endomorphisms, complex multiplication.
- Improve the point counting algorithms so as to be able to tackle larger problems. This includes significant work connected to polynomial systems.
- Seek improvements on the computation of discrete logarithms on curves, including by identifying weak instances of this problem.

3.3. Computer Arithmetic

Computer arithmetic is part of the common background of all team members, and is naturally ubiquitous in the two previous application domains mentioned. However involved the mathematical objects considered may be, dealing with them first requires to master more basic objects: integers, finite fields, polynomials, and real and complex floating-point numbers. Libraries such as GNU MP, GNU MPFR, GNU MPC do an excellent job for these, both for small and large sizes (we rarely, if ever, focus on small-precision floating-point data, which explains our lack of mention of libraries relevant to it).

Most of our involvement in subjects related to computer arithmetic is to be understood in connection to our applications to the Number Field Sieve and to abelian varieties. As such, much of the research work we envision will appear as side-effects of developments in these contexts. On the topic of arithmetic work *per se*:

- We will seek algorithmic and practical improvements to the most basic algorithms. That includes for example the study of advances algorithms for integer multiplication, and their practical reach.
- We will continue to work on the arithmetic libraries in which we have crucial involvement, such as GNU MPFR, GNU MPC, GF2X, MPFQ, and also GMP-ECM.

3.4. Polynomial Systems

Systems of polynomial equations have been part of the cryptographic landscape for quite some time, with applications to the cryptanalysis of block and stream ciphers, as well as multivariate cryptographic primitives.

Polynomial systems arising from cryptology are usually not generic, in the sense that they have some distinct structural properties, such as symmetries, or bi-linearity for example. During the last decades, several results have shown that identifying and exploiting these structures can lead to dedicated Gröbner bases algorithms that can achieve large speedups compared to generic implementations [27], [26].

Solving polynomial systems is well done by existing software, and duplicating this effort is not relevant. However we develop test-bed open-source software for ideas relevant to the specific polynomial systems that arise in the context of our applications. The TinyGB software, that we describe further in 6.3, is our platform to test new ideas.

We aim to work on the topic of polynomial system solving in connection with our involvement in the aforementioned topics.

- We have high expertise on Elliptic Curve Discrete Logarithm Problem on small characteristic finite fields, because it also involves highly structured polynomial systems. While so far we have not contributed to this hot topic, this could of course change in the future.
- Recent hirings (Minier) are likely to lead the team to study particular polynomial systems in context which are more related to symmetric key cryptography.
- More centered on polynomial systems *per se*, we will mainly pursue the study of the specificities of the polynomial systems that are strongly linked to our targeted applications, and for which we have significant expertise [27], [26]. We also want to see these recent results provide practical benefits compared to existing software, in particular for systems relevant for cryptanalysis.

4. Application Domains

4.1. Better Awareness and Avoidance of Cryptanalytic Threats

Our study of the Number Field Sieve family of algorithms aims at showing how the threats underlying various supposedly hard problems are real. Our record computations, as well as new algorithms, contribute to having a scientifically accurate assessment of the feasibility limit for these problems, given academic computing resources. The data we provide in this way is a primary ingredient for government agencies whose purpose includes guidance for the choice of appropriate cryptographic primitives. For example the French ANSSI [0], German BSI, or the NIST [0] in the United States base their recommendations on such computational achievements.

The software we make available to achieve these cryptanalytic computations also allows us to give cost estimates for potential attacks to cryptographic systems that are taking the security/efficiency/legacy compatibility trade-offs too lightly. Attacks such as LogJam [22] are understood as being serious concerns thanks to our convincing proof-of-concepts. In the LogJam context, this impact has led to rapid worldwide security advisories and software updates that eventually defeat some potential intelligence threats and improve confidentiality of communications.

[0] In [23], the minimal recommended RSA key size is 2048 bits for an usage up to 2030. See also Annex B, in particular Section B.1 “Records de calculs cryptographiques”.

[0] The work [32] is one of the only two academic works cited by NIST in the initial version (2011) of the report [36].

4.2. Promotion of Better Cryptography

We also promote the switch to algebraic curves as cryptographic primitives. Those offer nice speed and excellent security, while primitives based on elementary number theory (integer factorization, discrete logarithm in finite fields), which underpin e.g., RSA, are gradually forced to adopt unwieldy key sizes so as to comply with the desired security guarantees of modern cryptography. Our contributions to the ultimate goal of having algebraic curves eventually take over the cryptographic landscape lie in our fast arithmetic contributions, our contributions to the point counting problem, and more generally our expertise on the diverse surrounding mathematical objects, or on the special cases where the discrete logarithm problem is not hard enough and should be avoided.

We also promote cryptographically sound electronic voting, for which we develop the Belenios prototype software, (licensed under the AGPL). It depends on research made in collaboration with the PESTO team, and provides stronger guarantees than current state of the art.

4.3. Key Software Tools

The vast majority of our work is eventually realized as software. We can roughly categorize it in two groups. Some of our software covers truly fundamental objects, such as the GNU MPFR, GNU MPC, GF2X, or MPFQ packages. To their respective extent, these software packages are meant to be included or used in broader projects. For this reason, it is important that the license chosen for this software allows proper reuse, and we favor licenses such as the LGPL, which is not restrictive. We can measure the impact of this software by the way it is used in e.g., the GNU Compiler Collection (GCC), in Victor Shoup's Number Theory Library (NTL), or in the Sage computer algebra system. The availability of these software packages in most Linux distributions is also a good measure for the impact of our work.

We also develop more specialized software. Our flagship software package is Cado-NFS, and we also develop some others with various levels of maturity, such as GMP-ECM, CMH, or Belenios, aiming at quite diverse targets. Within the lifespan of the CARAMBA project, we expect more software packages of this kind to be developed, specialized towards tasks relevant to our research targets: important mathematical structures attached to genus 2 curves, generation of cryptographically secure curves, or tools for attacking cryptographically hard problems. Such software both illustrates our algorithms, and provides a base on which further research work can be established. Because of the very nature of these specialized software packages as research topics in their own right, needing both to borrow material from other projects, and being possible source of inspiring material for others, it is again important that these be developed in a free and open-source development model.

5. Highlights of the Year

5.1. Highlights of the Year

The Caramba project-team was created on January 1st, 2016!

In October 2016, Pierrick Gaudry and Emmanuel Thomé, together with colleagues from the University of Pennsylvania (USA), have performed a discrete logarithm computation of a 1024-bit trapdoored prime [18].

6. New Software and Platforms

6.1. Belenios

Belenios - Verifiable online voting system
KEYWORD: E-voting
FUNCTIONAL DESCRIPTION

Belenios is an online voting system that provides confidentiality and verifiability. End-to-end verifiability relies on the fact that the ballot box is public (voters can check that their ballots have been taken into account) and on the fact that the tally is publicly verifiable (anyone can recount the votes). Confidentiality relies on the encryption of the votes and the distribution of the decryption key.

Belenios builds upon Helios, a voting protocol used in several elections. The main design enhancement of Belenios vs Helios is that the ballot box can no longer add (fake) ballots, due to the use of credentials.

In 2016 our online platform has been used for several elections, for instance: representatives at the "comité de centre" in several Inria research centers, at the "conseil de laboratoire" at IRISA, and for the head of the "GT Calcul Formel" of the GDR-IM.

- Participants: Pierrick Gaudry, Stéphane Glondu and Véronique Cortier
- Partners: CNRS - Inria
- Contact: Stéphane Glondu
- URL: http://belenios.gforge.inria.fr/

6.2. Kalray-ECM

KEYWORDS: Factorization - Kalray
FUNCTIONAL DESCRIPTION

Implementation of the factorization algorithm based on elliptic curves (ECM) for the MPPA-256 Kalray processor.

- Authors: Jérémie Detrey, Pierrick Gaudry and Masahiro Ishii
- Partner: Nara Institute of Science and Technology, Japan
- Contact: Jérémie Detrey
- URL: https://gforge.inria.fr/projects/kalray-ecm

6.3. TinyGB

- Author: Pierre-Jean Spaenlehauer
- Contact: Pierre-Jean Spaenlehauer
- URL: https://gforge.inria.fr/projects/tinygb/
- Licence: LGPL-3.0+

`TinyGB` is a software implementing tools for computing Gröbner bases of ideals in polynomial rings over finite fields. It has been released in April 2016.

It is not competitive with state-of-art software for computations over small prime fields. However, for polynomial systems over $\mathbb{Z}/p\mathbb{Z}$, with $p > 2^{31}$, its timings are competitive with the computer algebra system `Magma-2.22-2` (although the `Magma` is much better in terms of memory requirements). This is due to the fact that `TinyGB` relies on the library `MPFQ` (developed in the Caramba team) for the efficient arithmetic over large prime fields. For instance, computing the grevlex Gröbner basis of a system of 13 dense homogeneous quadratic equations in 13 variables over the field $\mathbb{Z}/(2^{31}+11)\mathbb{Z}$ can be achieved within 907 seconds with `TinyGB`, whereas `Magma-2.22-2` requires 4459 seconds (on an Intel Core i5-4590@3.30GHz).

The distribution of `TinyGB` contains the libraries `OpenBLAS`, `FFLAS-FFPACK` and `MPFQ`.

7. New Results

7.1. Collecting Relation for the Number Field Sieve in Medium Characteristic

Participants: Pierrick Gaudry, Laurent Grémy [contact], Marion Videau.

We study the relation collection of NFS in medium characteristic, especially in $\mathrm{GF}(p^6)$ [4]. We compare different polynomial selections that affect drastically the relation collection step, by giving the explicit formula in 3 dimensions of two functions to select the best polynomials. For the relation collection, we design new sieve algorithms in 3 dimensions and do the practical comparison of the different polynomial selections for different p. Finally, we perform the relation collection step for a field of 389 bits in 800 days, the largest computed relation collection in this type of field.

7.2. Recent Progress on the Elliptic Curve Discrete Logarithm Problem

Participant: Pierrick Gaudry [contact].

A survey on the elliptic curve discrete logarithm problem has been written in collaboration with S. Galbraith (Auckland). It appeared in a special issue of DCC [3], for the 25th birthday of the journal.

7.3. A Modified Block Lanczos Algorithm with Fewer Vectors

Participant: Emmanuel Thomé [contact].

In the context of a book project entitled "Topics in Computational Number Theory inspired by Peter L. Montgomery" (edited by Joppe W. Bos and Arjen K. Lenstra), E. Thomé contributed a chapter on "the Block Lanczos algorithm" (owed to Peter L. Montgomery [35]). This was the occasion to rework and streamline the presentation of the block Lanczos algorithm. In fact, several new characteristics of the algorithm were obtained in this process: a version adapted to homogeneous systems, an improvement on the memory footprint of the algorithm, and a heuristic justification for the success probability of the algorithm. While the collated book is still not published yet (publication is expected in 2017), the chapter is published in preprint form as [14].

7.4. Factorization of RSA-220 with CADO-NFS

Participants: Pierrick Gaudry, Emmanuel Thomé, Paul Zimmermann [contact].

In May 2016 we have completed with CADO-NFS the factorization of RSA-220 [15], which was started in December 2013. The sieving was completed in September 2014, and the first phase of the linear algebra (`krylov`) in October 2014. However we had to improve CADO-NFS to be able to run the `lingen` sub-step of the linear algebra. This was completed in January 2016, and the end of the factorization ran smoothly. This factorization is the largest one done with CADO-NFS, and the third largest one overall, after RSA-768 (232 digits) factored in December 2009, and $3^{697}+1$ (221 digits) factored by NFS@Home in February 2015.

7.5. Linear Time Interactive Certificates for the Minimal Polynomial and the Determinant of a Sparse Matrix

Participant: Emmanuel Thomé [contact].

Following discussion with Jean-Guillaume Dumas which began in March 2015 on the topic of computing checkpoints for the `krylov` step of the block Wiedemann algorithm, we determined that a scheme very similar to this checkpointing technique (originally designed to spot data corruption errors) was able to provide a proving algorithm —in the cryptographic sense— for the computation of the minimal polynomial of a sparse matrix, or for its determinant. This led to a joint paper with Jean-Guillaume Dumas, Erich Kaltofen and Gilles Villard, published at ISSAC 2016 [8].

7.6. A Kilobit Hidden SNFS Discrete Logarithm Computation

Participants: Pierrick Gaudry, Emmanuel Thomé [contact].

In collaboration with Josh Fried and Nadia Heninger from University of Pennsylvania, we worked on discrete logarithm computation modulo primes of a special form, amenable to computation with the Special Number Field Sieve (SNFS). Our original interest in this question came from the observation that primes which are conspicuous SNFS targets *are* found in the wild, as we observed in the context of the LogJam attack in 2015. We first ran a test computation on such a prime in March ($p = 2^{784} - 2^{28} + 1027679$, found in the LibTomcrypt library. For modern cryptographic uses, such a prime qualifies undoubtedly as "not good'). Based on the computational data obtained, and on further work, we expanded to larger sizes. We crafted a prime which was chosen as a "best case" for SNFS, yet with the property that this SNFS-optimality cannot be detected. We call such primes "trapdoored primes". We showed that computing discrete logarithms modulo trapdoored primes is entirely feasible for 1024-bit primes. In the article [18], we also showed that there are primes which are found in the wild (e.g., in RFC 5114) which could plausibly be trapdoored primes, given that no justification of their origin is provided. In fact, while cryptographic best practice is to provide "rigid" choices whenever random choices are to be set publicly, the sad truth is that random data lacking a justification is found quite often.

In the context of [18], we also put into practice an improvement of the implementation of the block Wiedemann algorithm in Cado-NFS, that allowed to reduce the time for the linear algebra computation significantly.

7.7. Solving Discrete Logarithms on a 170-bit MNT Curve by Pairing Reduction

Participants: Aurore Guillevic [contact], Emmanuel Thomé [contact].

The project of computing discrete logarithms in finite fields of the form GF(p^n) for small n comes from the need to estimate precisely the security level of pairing-based cryptography. After the two record computations of 2014 and 2015 in GF(p^2) of 160 and 180 decimal digits (532 and 597 bits) we investigated GF(p^3) and took a real-life elliptic curve proposed in 2001 by Miyaji, Nakabayashi and Takano (MNT-3 curve). Thanks to a pairing computation (in few milliseconds), a discrete logarithm computation in the 170-bit MNT-3 curve, which is hard, can be done instead by a discrete logarithm computation in GF(p^3) of 508 bits, which is much faster. This computation involved Aurore Guillevic (post-doctoral fellow in 2016 at the University of Calgary, Canada), Emmanuel Thomé, and François Morain (LIX/École Polytechnique/Inria Saclay, GRACE team). The computation took 2.97 years in total: 1.81 years for the relation collection, 1.16 years for the linear algebra and 2 days for the individual discrete logarithm computation. The work was presented at the Selected Areas in Cryptography conference in Newfoundland, Canada, and published in the proceedings [11].

The next step will be to adapt the new NFS variant called Extended-Tower-NFS to attack MNT-4 and MNT-6 curves, which means computing discrete logarithms in GF(p^4) and GF(p^6). This new challenge will require the higher dimension sieve developed by Laurent Grémy.

7.8. Computing Jacobi's Theta in Quasi-linear Time

Participant: Hugo Labrande [contact].

Most of the results have been obtained in 2015. The article was accepted for publication in 2016 [5].

We study the multiprecision computation of the theta function in genus 1, *i.e.,* the Jacobi theta function. The main result is that $\theta(z, \tau)$ can be computed in time that is quasi-linear in the precision P, using an algorithm which follows the same strategy as the case of theta-constants (Dupont, 2006). A thorough analysis of the precision loss is given in order to prove correctness.

Along with this work, we have publicly released an open source implementation of the algorithm in C (using the GNU MPC library). This implementation shows this algorithm is faster than a more naive approach for precisions greater than 300,000 digits.

7.9. Computing Theta Functions in Quasi-linear Time in Genus 2 and Above

Participants: Hugo Labrande, Emmanuel Thomé [contact].

We study the multiprecision computation of the theta function in genus 2. We extend the quasi-linear algorithm for Jacobi's theta to genus 2, generalizing the approach we undertook in previous work; this required finding workarounds, most notably for the choice of signs and for being able to apply Newton's method. We also give an outline of an algorithm for the theta function in genus g, but the workarounds we found in genus 2 would need to be generalized to this case before claiming any sort of result in genus g [6].

We released along with this work a Magma implementation of our fast genus 2 algorithm, along with an implementation of a somewhat naive (but previously state-of-the-art) algorithm for genus 2. Our results show that our algorithm is faster than the naive one for precisions greater than 3,000 digits.

7.10. Computing Small Certificates of Inconsistency of Quadratic Fewnomial Systems

Participant: Pierre-Jean Spaenlehauer [contact].

This is a joint work with Jean-Charles Faugère (Inria, EPI Polsys) and Jules Svartz (Inria EPI Polsys/Ministère Éducation Nationale). Most of the results have been obtained in 2015. This work was finalized and published in 2016 [10].

We study how Gröbner bases algorithms can be adapted to compute certificates that *quadratic fewnomial systems* (*i.e.*, systems in which only a small subset of monomials occur in the equations) do not have any solution. The main results are algorithms and complexity bounds which take into account the sparsity of the monomial support of the system, under some mild genericity assumptions on the coefficients of the systems.

7.11. Critical Point Computations on Smooth Varieties: Degree and Complexity Bounds

Participant: Pierre-Jean Spaenlehauer [contact].

This is a joint work with Mohab Safey El Din (Univ. Paris 6, EPI Polsys). This work led to a publication in the proceedings of the ISSAC conference [13].

Let $V \subset \mathbb{C}^n$ be an equidimensional algebraic set and g be an n-variate polynomial with rational coefficients. Computing the critical points of the map that evaluates g at the points of V is a cornerstone of several algorithms in real algebraic geometry and optimization. Under the assumption that the critical locus is finite and that the projective closure of V is smooth, we provide sharp upper bounds on the degree of the critical locus which depend only on $\deg(g)$ and the degrees of the generic polar varieties associated to V. Using these degree bounds and an algorithm due to Bank, Giusti, Heintz, Lecerf, Matera and Solernó, we derive complexity bounds which are quadratic in the degree bounds (up to logarithmic factors) and polynomial in all the other parameters of the problem.

7.12. Constructing Sparse Polynomial Systems with Many Positive Solutions

Participant: Pierre-Jean Spaenlehauer [contact].

This is a joint work with Frédéric Bihan (Univ. de Savoie, LAMA). Most of the results have been obtained in 2015 [25]; we improved the results during 2016.

Consider a regular triangulation of the convex-hull P of a set $\mathcal{A}$ of n points in $\mathbb{R}^d$, and a real matrix C of size $d \times n$. A version of Viro's method allows to construct from these data an unmixed polynomial system with support $\mathcal{A}$ and coefficient matrix C whose number of positive solutions is bounded from below by the number of d-simplices which are positively decorated by C (a d-simplex is positively decorated by C if the $d \times (d+1)$ sub-matrix of C corresponding to the simplex has a kernel vector all coefficients of which are positive). We show that all the d-simplices of a triangulation can be positively decorated if and only if the triangulation is balanced, which in turn is equivalent to the fact that its dual graph is bipartite. This allows us to identify, among classical families, monomial supports which admit maximally positive systems, giving some evidence in favor of a conjecture due to Bihan. We also use this technique in order to construct fewnomial systems with many positive solutions.

7.13. Modular Arithmetic and ECM on the Kalray MPPA-256 Processor

Participants: Jérémie Detrey [contact], Pierrick Gaudry.

In collaboration with Masahiro Ishii from the Nara Institute of Science and Technology, Nara (Japan) we have developed a fast modular arithmetic library for the Kalray MPPA-256, which is a many-core processor with a VLIW architecture. Carefully written assembly allowed us to obtain a close to optimal use of the computing units of all the cores for the multiprecision multiplication of integers. As an application, the ECM factoring algorithm was implemented on top of our library. The performances are very interesting compared to other architectures like GPU, especially in terms of power consumption [19].

7.14. Determinism and Computational Power of Real Measurement-based Quantum Computation

Participant: Luc Sanselme [contact].

This is a joint work with Simon Perdrix (CNRS, Carte Team at Loria). This work has begun in 2014.

The starting point for this work was about a problem in «Quantum cloud computing». A person with a classical resource wants to perform a quantum computation. To do so he asks some quantum resources to perform his computation. The difficult part is that he wants to be sure that the quantum resources he asks to perform his computation don't cheat and return him the good results. This kind of «Quantum cloud computing» is called interactive proofs. The quantum resources are called the provers. Real Measurement-based quantum computing (MBQC) has been used for interactive proofs by McKague.

Measurement-based quantum computing (MBQC) is a universal model for quantum computation. The combinatorial characterization of determinism in this model, powered by measurements, and hence, fundamentally probabilistic, is the cornerstone of most of the breakthrough results in this field. To answer our question, we needed to develop some tools in this MBQC field. The most general known sufficient condition for a deterministic MBQC to be driven is that the underlying graph of the computation has a particular kind of flow called Pauli flow. The necessity of the Pauli flow was an open question. We showed that the Pauli flow is necessary for real-MBQC, and not in general providing counter-examples for (complex) MBQC. We explored the consequences of this result for real MBQC and its applications. Real MBQC and more generally real quantum computing is known to be universal for quantum computing. In the interactive proofs developed by McKague, the two-prover case corresponds to real-MBQC on bipartite graphs. While (complex) MBQC on bipartite graphs are universal, the universality of real MBQC on bipartite graphs was an open question. We showed that real bipartite MBQC is not universal: we proved that all measurements of real bipartite MBQC can be parallelized. Therefore, real bipartite MBQC leads to constant depth computations. As a consequence, McKague techniques cannot lead to two-prover interactive proofs.

7.15. Fast Integer Multiplication Using Generalized Fermat Primes

Participants: Svyatoslav Covanov [contact], Emmanuel Thomé.

The paper [17] describes an algorithm for the multiplication of two n-bit integers. It achieves the best asymptotic complexity bound $O(n \log n \cdot 4^{\log^* n})$ under a hypothesis on the distribution of generalized Fermat primes of the form $r^{2^\lambda} + 1$. This hypothesis states that there always exists a sufficiently small interval in which we can find such a prime. Experimental results give evidence in favor of this assumption. This article has been submitted to Mathematics of Computation and some corrections, that have been requested, are processed currently.

7.16. Search for Primitive Trinomials

Participant: Paul Zimmermann [contact].

This is a joint work with Richard Brent (University of Newcastle, Australia).

We have performed a search for primitive trinomials $x^r + x^s + 1$ over $\mathrm{GF}(2)$ of degree $r = 42\,643\,801$, $r = 43\,112\,609$, $r = 57\,885\,161$ and $r = 74\,207\,281$, which are the new Mersenne prime exponents found by the GIMPS project. We found respectively 5, 4, 0 and 3 primitive trinomials [16], for example the three primitive trinomials of degree 74 207 281 are (with their reverse trinomials):

$$x^{74207281} + x^{9156813} + 1, \qquad x^{74207281} + x^{9999621} + 1, \qquad x^{74207281} + x^{30684570} + 1.$$

8. Bilateral Contracts and Grants with Industry

8.1. Training and Consulting with HTCS

The training and consulting activities begun in 2012 with the HTCS company have been pursued, and the existing contract has been renewed in identical form.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. PEPS JCJC INS2I SPICE

The SPICE proposal (“Systèmes Polynomiaux et calcul d’Indice sur les Courbes Elliptiques : indicateurs de complexité en petite caractéristique”) has been accepted in the PEPS JCJC INS2I program in 2016. It involves Pierre-Jean Spaenlehauer (CARAMBA) and Vanessa Vitse (Université Joseph Fourier). This project is coordinated by Vanessa Vitse.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organization

10.1.1.1. Member of the Organizing Committees

- Together with Anne-Lise Charbonnier (Inria Nancy – Grand Est), the Caramba team is organizing the "Journées Codage et Cryptographie 2017", whose objective is to regroup the French speaking community working on error-correcting codes and on cryptography. It is affiliated with the "Groupe de travail C2" of the GDR-IM.

10.1.2. Scientific Events Selection

10.1.2.1. Member of steering committees

- Pierrick Gaudry is a member of the steering committee of the Workshop on Elliptic Curve Cryptography (ECC).

10.1.2.2. Member of the Conference Program Committees

- Emmanuel Thomé was a member of the program committee of the 35th Annual International Conference on the Theory and Applications of Cryptographic Techniques (Eurocrypt 2016).
- Marine Minier was a member of the Program Committee of the conference MyCrypt 2016.
- Pierrick Gaudry was a member of the Program Committee of the conference Selected Areas in Cryptography SAC 2016 and of EUROCRYPT 2017.
- Paul Zimmermann was a member of the Program Committee of the International Workshop on the Arithmetic of Finite Fields (WAIFI 2016).

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- Pierrick Gaudry is a member of the editorial board of the journal Applicable Algebra in Engineering, Communication and Computing.

10.1.3.2. Reviewer - Reviewing Activities

Members of the project-team did share in reviewing submissions to renowned conferences and journals. Actual publications venues are not disclosed for anonymity reasons.

10.1.4. Invited Talks

- Emmanuel Thomé was invited as a Distinguished Lecturer for the Computer and Information Security Seminar at the University of Pennsylvania in November 2016.
- Pierrick Gaudry was invited speaker at the YACC 2016 conference in Porquerolles, at the workshop "Mathematical Structures for Cryptography" in Leiden (Netherlands), and at the "Journées Aléa 2016" in Marseille.

10.1.5. Other committees

- Jérémie Detrey is chairing the *Commission des Utilisateurs des Moyens Informatiques* (CUMI) of the Inria Nancy – Grand Est research center.
- Emmanuel Thomé is a member of
  - the management committee for the research project "CPER Cyberentreprises" (co-chair).
  - the *Comité Local Hygiène, Sécurité, et Conditions de Travail* of the Inria Nancy – Grand Est research center.

- Pierrick Gaudry is vice-head of the *Commission de mention Informatique* of the *École doctorale IAEM* of the University of Lorraine;
- Pierre-Jean Spaenlehauer is a member of the *Commission développement technologique* (CDT) of the Inria Nancy – Grand Est research center.
- Paul Zimmermann is member of the Scientific Committee of the EXPLOR *Mésocentre*, and was member until August of the Inria Evaluation Board and the CoSI (*Commission Scientifique*).

10.1.6. Research Administration

- Laurent Grémy is a member of the *Conseil de laboratoire* of the Loria.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Master: Jérémie Detrey, *Sécurité des systèmes d'information*, 6 hours (practical sessions), M2 Informatique, Université de Lorraine, Faculté des sciences et technologies, Vandœuvre-les-Nancy, France.

Master: Pierre-Jean Spaenlehauer, *Introduction à la cryptographie*, 18h eq. TD, M1 Informatique, Université de Lorraine, Faculté des sciences et technologies, Vandœuvre-les-Nancy, France.

Master: Pierre-Jean Spaenlehauer, *Introduction à la sécurité des systèmes et à la cryptographie*, 32h eq. TD, M2 Mathématiques IMOI, Université de Lorraine, Faculté des sciences et technologies, Vandœuvre-les-Nancy, France.

Master: Emmanuel Thomé, *Introduction to Cryptography*, 12 hours (lectures), M1, Télécom Nancy, Villers-lès-Nancy, France.

Master: Emmanuel Thomé, *Cryptography and Security*, 20 hours (lectures + exercises), M2, Télécom Nancy and École des Mines de Nancy, France.

Licence: Jérémie Detrey, *Méthodologie*, 24 hours (practical sessions), L1, Université de Lorraine, Faculté des sciences et technologies, Vandœuvre-les-Nancy, France.

Licence: Jérémie Detrey, *Sécurité des applications Web*, 2 hours (lecture), L1, Université de Lorraine, IUT Charlemagne, Nancy, France.

Jérémie Detrey, *Introduction à la sécurité et à la cryptographie*, 10 hours (lectures) + 10 hours (tutorial sessions) + 10 hours (practical sessions), L3, Université de Lorraine, Faculté des sciences et technologies, Vandœuvre-les-Nancy, France.

Licence: Pierrick Gaudry, *Méthodologie*, 48 hours (practical sessions), L1, Université de Lorraine, Faculté des sciences et technologies, Vandœuvre-lès-Nancy, France.

10.2.2. Supervision

Internship: Nicolas Levy, *Algorithmes de factorisation d'entiers basés sur la structure des corps quadratiques réels*, L3 ÉNS Lyon, June-July, Pierre-Jean Spaenlehauer.

Internship: Joshua Peigner, *Factorisation d'idéaux pour l'implantation du crible algébrique*, ÉNS Rennes, June-July, Emmanuel Thomé.

Internship: Robin Fedele, *Consolidation de la couche Python de CADO-NFS*, Univ. Lorraine, May-June, Paul Zimmermann.

Internship: Élise Tasso, *Étude comparative de divers algorithmes de friabilisation*, Mines Nancy, October-June (1 day each week), Pierrick Gaudry.

Ph.D. in progress: Simon Abelard, *Comptage de points de courbes algébriques sur les corps finis et interactions avec les systèmes polynomiaux*, Univ. Lorraine; since Sep. 2015, Pierrick Gaudry & Pierre-Jean Spaenlehauer.

Ph.D. in progress: Svyatoslav Covanov, *Algorithmes de multiplication : complexité bilinéaire et méthodes asymptotiquement rapides*, since Sep. 2014, Jérémie Detrey et Emmanuel Thomé.

Ph.D. in progress: Laurent Grémy, *Analyse et optimisation d'algorithmes de cribles arithmétiques*, since Oct. 2013, Pierrick Gaudry & Marion Videau.

Ph.D. defended: Hugo Labrande, *Explicit computation of the Abel-Jacobi map and its inverse* [1], defended on November 14th, 2016.

10.2.3. Juries

Marine Minier: reviewer of the PhD *Implantation sécurisée de protocoles cryptographiques basés sur les codes correcteurs d'erreurs* by Tania Richmont defended at Univ. Jean Monnet Saint-Etienne, October 24th, 2016.

Pierrick Gaudry: reviewer of the PhD *Computational Aspects of Jacobians of Hyperelliptic Curves* by Alina Dudeanu defended at EPFL, Switzerland; member of the jury for the PhD of Florent Ulpat Rovetta (Marseille) and of Hugo Labrande (Nancy).

Emmanuel Thomé: reviewer (and president of jury) of the Habilitation Thesis *Contributions à la Résolution Algébrique et Applications en Cryptologie* by Guénaël Renault, defended at University Pierre et Marie Curie, December 8th, 2016.

Emmanuel Thomé: jury member (advisor) for the PhD of Hugo Labrande (see above).

10.3. Popularization

- Laurent Grémy and Pierre-Jean Spaenlehauer have animated a stand in the "Village des Sciences du Loria" in March 2016.
- Laurent Grémy and Pierre-Jean Spaenlehauer have animated a stand during the celebration of the Loria's 40 years anniversary in June 2016.
- Pierrick Gaudry organized and participated to a debate fed by excerpts from movies on the topic of cryptography and privacy in October 2016.

11. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] H. LABRANDE.*Explicit computation of the Abel-Jacobi map and its inverse*, Université de Lorraine ; University of Calgary, November 2016, https://tel.archives-ouvertes.fr/tel-01403849.

Articles in International Peer-Reviewed Journal

[2] C. CHEN, S. COVANOV, F. MANSOURI, R. H. C. MOIR, M. MORENO MAZA, N. XIE, Y. XIE.*The Basic Polynomial Algebra Subprograms*, in "ACM Communications in Computer Algebra", November 2016 [*DOI :* 10.1145/3015306.3015312], https://hal.archives-ouvertes.fr/hal-01404718.

[3] S. GALBRAITH, P. GAUDRY.*Recent progress on the elliptic curve discrete logarithm problem*, in "Designs, Codes and Cryptography", 2016, vol. 78, n^o 1, p. 51-72 [*DOI :* 10.1007/s10623-015-0146-7], https://hal.inria.fr/hal-01215623.

[4] P. GAUDRY, L. GRÉMY, M. VIDEAU.*Collecting relations for the number field sieve in $GF(p^6)$*, in "LMS Journal of Computation and Mathematics", 2016, vol. 19, p. 332 - 350 [*DOI :* 10.1112/S1461157016000164], https://hal.inria.fr/hal-01273045.

[5] H. LABRANDE.*Computing Jacobi's θ in quasi-linear time*, in "Mathematics of Computation", November 2016, https://hal.inria.fr/hal-01227699.

[6] H. LABRANDE, E. THOMÉ.*Computing theta functions in quasi-linear time in genus 2 and above*, in "LMS Journal of Computation and Mathematics", August 2016, vol. 19, n^{o} A, p. 163-177 [*DOI :* 10.1112/S1461157016000309], https://hal.inria.fr/hal-01277169.

[7] J.-P. ÉCHARD, P. GAUDRY.*An harmonious encoding of instrument values by a 19th century Parisian violin dealer*, in "Cryptologia", 2016, À paraître, https://hal.inria.fr/hal-01393625.

International Conferences with Proceedings

[8] J.-G. DUMAS, E. KALTOFEN, E. THOMÉ, G. VILLARD.*Linear Time Interactive Certificates for the Minimal Polynomial and the Determinant of a Sparse Matrix*, in "International Symposium on Symbolic and Algebraic Computation", Waterloo, Canada, X.-S. GAO (editor), ISSAC'2016, Proceedings of the 2016 ACM International Symposium on Symbolic and Algebraic Computation, ACM, July 2016, https://hal.archives-ouvertes.fr/hal-01266041.

[9] N. EYROLLES, L. GOUBIN, M. VIDEAU.*Defeating MBA-based Obfuscation*, in "2nd International Workshop on Software PROtection", Vienna, Austria, ACM (editor), October 2016 [*DOI :* 10.1145/2995306.2995308], https://hal.archives-ouvertes.fr/hal-01388109.

[10] J.-C. FAUGÈRE, P.-J. SPAENLEHAUER, J. SVARTZ.*Computing Small Certificates of Inconsistency of Quadratic Fewnomial Systems*, in "International Symposium on Symbolic and Algebraic Computation (ISSAC 2016)", Waterloo, Canada, ACM, July 2016, p. 223-230 [*DOI :* 10.1145/2930889.2930927], https://hal.inria.fr/hal-01314651.

[11] A. GUILLEVIC, F. MORAIN, E. THOMÉ.*Solving discrete logarithms on a 170-bit MNT curve by pairing reduction*, in "Selected Areas in Cryptography 2016", St. John's, Canada, R. AVANZI, H. HEYS (editors), Selected Areas in Cryptography 2016, Springer, August 2016, to appear in the Lecture Notes in Computer Science (LNCS), https://hal.inria.fr/hal-01320496.

[12] A. GUINET, N. EYROLLES, M. VIDEAU.*Arybo: Manipulation, Canonicalization and Identification of Mixed Boolean-Arithmetic Symbolic Expressions*, in "GreHack 2016", Grenoble, France, Proceedings of GreHack 2016, November 2016, https://hal.archives-ouvertes.fr/hal-01390528.

[13] M. SAFEY EL DIN, P.-J. SPAENLEHAUER.*Critical Point Computations on Smooth Varieties: Degree and Complexity bounds*, in "International Symposium on Symbolic and Algebraic Computation (ISSAC)", Waterloo, Canada, July 2016, p. 183–190 [*DOI :* 10.1145/2930889.2930929], https://hal.inria.fr/hal-01312750.

Scientific Books (or Scientific Book chapters)

[14] E. THOMÉ.*A modified block Lanczos algorithm with fewer vectors*, in "Topics in Computational Number Theory inspired by Peter L. Montgomery", Cambridge University Press, 2016, https://hal.inria.fr/hal-01293351.

Other Publications

[15] S. BAI, P. GAUDRY, A. KRUPPA, E. THOMÉ, P. ZIMMERMANN.*Factorisation of RSA-220 with CADO-NFS*, May 2016, working paper or preprint, https://hal.inria.fr/hal-01315738.

[16] R. P. BRENT, P. ZIMMERMANN.*Twelve new primitive binary trinomials*, October 2016, working paper or preprint, https://hal.inria.fr/hal-01378493.

[17] S. COVANOV, E. THOMÉ.*Fast integer multiplication using generalized Fermat primes*, January 2016, working paper or preprint, https://hal.inria.fr/hal-01108166.

[18] J. FRIED, P. GAUDRY, N. HENINGER, E. THOMÉ.*A kilobit hidden SNFS discrete logarithm computation*, September 2016, working paper or preprint, https://hal.inria.fr/hal-01376934.

[19] M. ISHII, J. DETREY, P. GAUDRY, A. INOMATA, K. FUJIKAWA.*Fast Modular Arithmetic on the Kalray MPPA-256 Processor for an Energy-Efficient Implementation of ECM*, April 2016, working paper or preprint, https://hal.inria.fr/hal-01299697.

[20] S. PERDRIX, L. SANSELME.*Determinism and Computational Power of Real Measurement-based Quantum Computation*, October 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01377339.

[21] P. ZIMMERMANN, F. BASTIEN.*Paul Zimmermann - CADO-NFS: Atelier PARI/GP 2016*, January 2016, https://hal.archives-ouvertes.fr/medihal-01346718.

References in notes

[22] D. ADRIAN, K. BHARGAVAN, Z. DURUMERIC, P. GAUDRY, M. GREEN, J. ALEX HALDERMAN, N. HENINGER, D. SPRINGALL, E. THOMÉ, L. VALENTA, B. VANDERSLOOT, E. WUSTROW, S. ZANELLA-BÉGUELIN, P. ZIMMERMANN.*Imperfect Forward Secrecy: How Diffie-Hellman fails in practice*, in "CCS'15", ACM, 2015, p. 5–17, http://dl.acm.org/citation.cfm?doid=2810103.2813707.

[23] AGENCE NATIONALE DE LA SÉCURITÉ DES SYSTÈMES D'INFORMATION.*Référentiel général de sécurité, annexe B1*, 2014, Version 2.03, http://www.ssi.gouv.fr/uploads/2014/11/RGS_v-2-0_B1.pdf.

[24] R. BARBULESCU, P. GAUDRY, A. JOUX, E. THOMÉ.*A heuristic quasi-polynomial algorithm for discrete logarithm in finite fields of small characteristic*, in "Eurocrypt 2014", Copenhagen, Denmark, P. Q. NGUYEN, E. OSWALD (editors), Springer, May 2014, vol. 8441, p. 1-16 [*DOI :* 10.1007/978-3-642-55220-5_1], https://hal.inria.fr/hal-00835446.

[25] F. BIHAN, P.-J. SPAENLEHAUER.*Sparse polynomial systems with many positive solutions from bipartite simplicial complexes*, 2015, arXiv preprint arXiv:1510.05622.

[26] J.-C. FAUGÈRE, P.-J. SPAENLEHAUER, J. SVARTZ.*Sparse Gröbner bases: the unmixed case*, in "ISSAC 2014", K. NABESHIMA (editor), ACM, 2014, p. 178–185, Proceedings.

[27] J.-C. FAUGÈRE, M. SAFEY EL DIN, P.-J. SPAENLEHAUER.*Gröbner Bases of Bihomogeneous Ideals generated by Polynomials of Bidegree* $(1,1)$*: Algorithms and Complexity*, in "J. Symbolic Comput.", 2011, vol. 46, n^{o} 4, p. 406–437.

[28] P. GAUDRY, É. SCHOST.*Genus 2 point counting over prime fields*, in "J. Symbolic Comput.", 2011, vol. 47, n^{o} 4, p. 368–400.

[29] R. GRANGER, T. KLEINJUNG, J. ZUMBRÄGEL.*On the Powers of 2*, 2014, Cryptology ePrint Archive report, http://eprint.iacr.org/2014/300.

[30] F. GÖLOGLU, R. GRANGER, J. MCGUIRE.*On the Function Field Sieve and the Impact of Higher Splitting Probabilities*, in "CRYPTO 2013", R. CANETTI, J. A. GARAY (editors), Lecture Notes in Comput. Sci., Springer–Verlag, 2013, vol. 8043, p. 109–128, Proceedings, Part II.

[31] A. JOUX.*A New Index Calculus Algorithm with Complexity* $L(1/4+o(1))$ *in Small Characteristic*, in "Selected Areas in Cryptography – SAC 2013", T. LANGE, K. LAUTER, P. LISONĚK (editors), Lecture Notes in Comput. Sci., Springer–Verlag, 2014, vol. 8282, p. 355–379, Proceedings, http://dx.doi.org/10.1007/978-3-662-43414-7_18.

[32] T. KLEINJUNG, K. AOKI, J. FRANKE, A. K. LENSTRA, E. THOMÉ, J. BOS, P. GAUDRY, A. KRUPPA, P. L. MONTGOMERY, D. A. OSVIK, H. TE RIELE, A. TIMOFEEV, P. ZIMMERMANN.*Factorization of a 768-bit RSA modulus*, in "CRYPTO 2010", T. RABIN (editor), Lecture Notes in Comput. Sci., Springer–Verlag, 2010, vol. 6223, p. 333–350, Proceedings.

[33] N. KOBLITZ, A. J. MENEZES.*A Riddle Wrapped in an Enigma*, 2015, Cryptology ePrint Archive report, http://eprint.iacr.org/2015/1018.

[34] A. LANGLEY, M. HAMBURG, S. TURNER.*Elliptic Curves for Security*, 2016, RFC 7748, https://tools.ietf.org/html/rfc7748.

[35] P. L. MONTGOMERY.*A block Lanczos algorithm for finding dependencies over* $\mathrm{GF}(2)$, in "EUROCRYPT '95", L. C. GUILLOU, J.-J. QUISQUATER (editors), Lecture Notes in Comput. Sci., 1995, vol. 921, p. 106–120, Proceedings.

[36] NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY.*Transitions: Recommendation for Transitioning the Use of Cryptographic Algorithms and Key Lengths*, 2011, First revision, http://dx.doi.org/10.6028/NIST.SP.800-131A.

[37] NATIONAL SECURITY AGENCY.*Cryptography Today*, 2015, https://www.nsa.gov/ia/programs/suiteb_cryptography/index.shtml.

Team CARTE

Theoretical adverse computations, and safety

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
Nancy - Grand Est

THEME
Security and Confidentiality

Table of contents

Team CARTE

Creation of the Project-Team: 2009 January 01, updated into Team: 2016 January 01

Keywords:

Computer Science and Digital Science:

1.1.11. - Quantum architectures
2.3.2. - Cyber-physical systems
2.4.3. - Proofs
7.2. - Discrete mathematics, combinatorics
7.4. - Logic in Computer Science
7.5. - Geometry, Topology
7.8. - Information theory
7.9. - Graph theory
7.13. - Quantum algorithms

Other Research Topics and Application Domains:

9.4.1. - Computer science
9.4.2. - Mathematics
9.4.3. - Physics

1. Members

Research Scientists

Nazim Fatès [Inria, Researcher]
Isabelle Gnaedig [Inria, Researcher]
Mathieu Hoyrup [Inria, Researcher]
Simon Perdrix [CNRS, Researcher]
Quanlong Wang [Univ. Lorraine, Starting Research position, until Mar 2016]

Faculty Members

Emmanuel Jeandel [Team leader, Univ. Lorraine, Professor, HDR]
Emmanuel Hainry [Univ. Lorraine, Associate Professor]
Romain Péchoux [Univ. Lorraine, Associate Professor]

Technical Staff

Jean-Philippe Eisenbarth [Univ. Lorraine, from Mar 2016]

PhD Students

Hubert Godfroy [Univ. Lorraine]
Pierre Mercuriali [Univ. Lorraine, from Mar 2016]
Renaud Vilmart [Univ. Lorraine, from Mar 2016]

Post-Doctoral Fellow

Martin Delacourt [Univ. Lorraine, ATER, until Aug 2016]

Administrative Assistants

Emmanuelle Deschamps [Inria]
Delphine Hubert [Univ. Lorraine]
Martine Kuhlmann [CNRS]

Others

Arinta Auza [Inria, M2 Intern, from Mar 2016 until Jul 2016]
Walid Gomaa [Egypt-Japan Univ. of Science and Technology (Alexandria), Visiting Associate Professor, until Sep 2016]
Julien Oury-Nogues [Inria, M2 Intern, from Jun 2016 until Sep 2016]

2. Overall Objectives

2.1. Overall Objectives

The aim of the CARTE research team is to take into account adversity in computations, which is implied by actors whose behaviors are unknown or unclear. We call this notion adversary computation.

The project combines two approaches. The first one is the analysis of the behavior of systems, using tools coming from Continuous Computation Theory. The second approach is to build defenses with tools coming from logic, rewriting and, more generally, from Programming Theory.

The activities of the CARTE team are organized around two research actions:

- Computation over Continuous Structures
- Computer Virology.

3. Research Program

3.1. Computer Virology

From a historical point of view, the first official virus appeared in 1983 on Vax-PDP 11. At the same time, a series of papers was published which always remains a reference in computer virology: Thompson [71], Cohen [42] and Adleman [29]. The literature which explains and discusses practical issues is quite extensive [46], [48]. However, there are only a few theoretical/scientific studies, which attempt to give a model of computer viruses.

A virus is essentially a self-replicating program inside an adversary environment. Self-replication has a solid background based on works on fixed point in λ-calculus and on studies of von Neumann [76]. More precisely we establish in [38] that Kleene's second recursion theorem [60] is the cornerstone from which viruses and infection scenarios can be defined and classified. The bottom line of a virus behavior is

1. a virus infects programs by modifying them,
2. a virus copies itself and can mutate,
3. it spreads throughout a system.

The above scientific foundation justifies our position to use the word virus as a generic word for self-replicating malwares. There is yet a difference. A malware has a payload, and virus may not have one. For example, a worm is an autonomous self-replicating malware and so falls into our definition. In fact, the current malware taxonomy (virus, worms, trojans, ...) is unclear and subject to debate.

3.2. Computation over continuous structures

Classical recursion theory deals with computability over discrete structures (natural numbers, finite symbolic words). There is a growing community of researchers working on the extension of this theory to continuous structures arising in mathematics. One goal is to give foundations of numerical analysis, by studying the limitations of machines in terms of computability or complexity, when computing with real numbers. Classical questions are : if a function $f : \mathbb{R} \to \mathbb{R}$ is computable in some sense, are its roots computable? in which time? Another goal is to investigate the possibility of designing new computation paradigms, transcending the usual discrete-time, discrete-space computer model initiated by the Turing machine that is at the base of modern computers.

While the notion of a computable function over discrete data is captured by the model of Turing machines, the situation is more delicate when the data are continuous, and several non-equivalent models exist. In this case, let us mention computable analysis, which relates computability to topology [45], [74]; the Blum-Shub-Smale model (BSS), where the real numbers are treated as elementary entities [37]; the General Purpose Analog Computer (GPAC) introduced by Shannon [69]with continuous time.

3.3. Rewriting

The rewriting paradigm is now widely used for specifying, modelizing, programming and proving. It allows one to easily express deduction systems in a declarative way, and to express complex relations on infinite sets of states in a finite way, provided they are countable. Programming languages and environments with a rewriting based semantics have been developed ; see ASF+SDF [39], MAUDE [41], and TOM [66].

For basic rewriting, many techniques have been developed to prove properties of rewrite systems like confluence, completeness, consistency or various notions of termination. Proof methods have also been proposed for extensions of rewriting such as equational extensions, consisting of rewriting modulo a set of axioms, conditional extensions where rules are applied under certain conditions only, typed extensions, where rules are applied only if there is a type correspondence between the rule and the term to be rewritten, and constrained extensions, where rules are enriched by formulas to be satisfied [32], [44], [70].

An interesting aspect of the rewriting paradigm is that it allows automatable or semi-automatable correctness proofs for systems or programs: the properties of rewriting systems as those cited above are translatable to the deduction systems or programs they formalize and the proof techniques may directly apply to them.

Another interesting aspect is that it allows characteristics or properties of the modeled systems to be expressed as equational theorems, often automatically provable using the rewriting mechanism itself or induction techniques based on completion [43]. Note that the rewriting and the completion mechanisms also enable transformation and simplification of formal systems or programs.

Applications of rewriting-based proofs to computer security are various. Approaches using rule-based specifications have recently been proposed for detection of computer viruses [72], [73]. For several years, in our team, we have also been working in this direction. We already proposed an approach using rewriting techniques to abstract program behaviors for detecting suspicious or malicious programs [34], [35].

4. Application Domains

4.1. Computer Virology

4.1.1. The theoretical track

It is rightful to wonder why there are only a few fundamental studies on computer viruses while it is one of the important flaws in software engineering. The lack of theoretical studies explains maybe the weakness in the anticipation of computer diseases and the difficulty to improve defenses. For these reasons, we do think that it is worth exploring fundamental aspects, and in particular self-reproducing behaviors.

4.1.2. The virus detection track

The crucial question is how to detect viruses or self-replicating malwares. Cohen demonstrated that this question is undecidable. The anti-virus heuristics are based on two methods. The first one consists in searching for virus signatures. A signature is a regular expression, which identifies a family of viruses. There are obvious defects. For example, an unknown virus will not be detected, like ones related to a 0-day exploit. We strongly suggest to have a look at the independent audit [47] in order to understand the limits of this method. The second one consists in analyzing the behavior of a program by monitoring it. Following [49], this kind of methods is not yet really implemented. Moreover, the large number of false-positive implies this is barely usable. To end this short survey, intrusion detection encompasses virus detection. However, unlike computer virology, which has a solid scientific foundation as we have seen, the IDS notion of “malwares” with respect to some security policy is not well defined. The interested reader may consult [67].

4.1.3. The virus protection track

The aim is to define security policies in order to prevent malware propagation. For this, we need (i) to define what is a computer in different programming languages and setting, (ii) to take into consideration resources like time and space. We think that formal methods like rewriting, type theory, logic, or formal languages, should help to define the notion of a formal immune system, which defines a certified protection.

4.1.4. The experimentation track

This study on computer virology leads us to propose and construct a "high security lab" in which experiments can be done in respect with the French law.

4.2. Computations and Dynamical Systems

4.2.1. Continuous computation theories

Understanding computation theories for continuous systems leads to studying hardness of verification and control of these systems. This has been used to discuss problems in fields as diverse as verification (see e.g., [31]), control theory (see e.g., [40]), neural networks (see e.g., [68]), and so on. We are interested in the formal decidability of properties of dynamical systems, such as reachability [59], the Skolem-Pisot problem [36], the computability of the ω-limit set [58]. Those problems are analogous to verification of safety properties.

Contrary to computability theory, complexity theory over continuous spaces is underdeveloped and not well understood. A central issue is the choice of the representation of objects by discrete data and its effects on the induced complexity notions. As for computability, it is well known that a representation is gauged by the topology it induces. However more structure is needed to capture the complexity notions: topologically equivalent representations may induce different classes of polynomial-time computable objects, e.g., developing a sound complexity theory over continuous structures would enable us to make abstract computability results more applicable by analyzing the corresponding complexity issues. We think that the preliminary step towards such a theory is the development of higher-order complexity, which we are currently carrying out.

In contrast with the discrete setting, it is of utmost importance to compare the various models of computation over the reals, as well as their associated complexity theories. In particular, we focus on the General Purpose Analog Computer of Claude Shannon [69], on recursive analysis [74], on the algebraic approach [65] and on Markov computability [61]. A crucial point for future investigations is to fill the gap between continuous and discrete computational models. This is one deep motivation of our work on computation theories for continuous systems.

4.2.2. Analysis and verification of adversary systems

The other research direction on dynamical systems we are interested in is the study of properties of adversary systems or programs, i.e., of systems whose behavior is unknown or indistinct, or which do not have classical expected properties. We would like to offer proof and verification tools, to guarantee the correctness of such systems. On one hand, we are interested in continuous and hybrid systems. In a mathematical sense, a hybrid system can be seen as a dynamical system, whose transition function does not satisfy the classical regularity hypotheses, like continuity, or continuity of its derivative. The properties to be verified are often expressed as reachability properties. For example, a safety property is often equivalent to (non-)reachability of a subset of unsure states from an initial configuration, or to stability (with its numerous variants like asymptotic stability, local stability, mortality, etc ...). Thus we will essentially focus on verification of these properties in various classes of dynamical systems.

We are also interested in rewriting techniques, used to describe dynamic systems, in particular in the adversary context. As they were initially developed in the context of automated deduction, the rewriting proof techniques, although now numerous, are not yet adapted to the complex framework of modelization and programming. An important stake in the domain is then to enrich them to provide realistic validation tools, both in providing finer rewriting formalisms and their associated proof techniques, and in developing new validation concepts in the adversary case, i.e., when usual properties of the systems like, for example, termination are not verified. For several years, we have been developing specific procedures for property proofs of rewriting, for the sake of programming, in particular with an inductive technique, already applied with success to termination under strategies [50], [51], [52], to weak termination [53], sufficient completeness [54] and probabilistic termination [56]. The last three results take place in the context of adversary computations, since they allow for proving that even a divergent program, in the sense where it does not terminate, can give the expected results. A common mechanism has been extracted from the above works, providing a generic inductive proof framework for properties of reduction relations, which can be parametrized by the property to be proved [55], [57]. Provided program code can be translated into rule-based specifications, this approach can be applied to correctness proof of software in a larger context. A crucial element of safety and security of software systems is the problem of resources. We are working in the field of Implicit Computational Complexity. Interpretation based methods like Quasi-interpretations (QI) or sup-interpretations, are the approach we have been developing these last years [62], [63], [64]. Implicit complexity is an approach to the analysis of the resources that are used by a program. Its tools come essentially from proof theory. The aim is to compile a program while certifying its complexity.

5. Highlights of the Year

5.1. Highlights of the Year

The Marie Curie RISE project *Computing with Infinite Data* coordinated by Dieter Spreen (Siegen University), in which Mathieu Hoyrup is participating, has been accepted. It will start in April 2017.

6. New Results

6.1. Quantum Computing

Participants: Simon Perdrix, Quanlong Wang.

- **ZX-calculus**

  The ZX-calculus is a powerful diagrammatic language for quantum mechanics and quantum information processing. The completeness of the ZX-calculus is crucial: the language would be complete if any equation involving two diagrams representing the same quantum evolution can be derived using the rules of the language. While the language is known to be incomplete in general with no obvious way to add some new rules [75], two interesting fragments have been studied: the $\pi/2$ and the $\pi/4$-fragments, obtained by restricting the angles of diagrams to be multiples of $\pi/2$ and $\pi/4$ respectively.

  The $\pi/4$-fragment is approximatively universal for quantum mechanics, i.e. any quantum evolution can be approximated with an arbitrary accuracy using a diagram involving only angles multiple of $\pi/4$. The completeness of this fragment was one of the main open question in this domain. We have proved that this fragment is incomplete. We exhibit a fairly simple equation called supplementarity and we prove that this equation cannot be derived in the ZX-calculus. We propose as a consequence, to add supplementarity to the set of rules of the ZX-calculus. This result has been published at MFCS 2016 [20].

  The $\pi/2$-fragment is not universal, even approximatively. However it corresponds to the so-called stabiliser quantum mechanics, an interesting fragment of quantum mechanics. The $pi/2$-fragment is known to be complete for stabiliser quantum mechanics [33]. We have proved recently that the rules of the language can be simplified, leading to a simpler set of axioms. Moreover we have proved that most of the remaining rules being necessary are the completeness of the $\pi/2$-fragment. This result has been published at QPL 2016 [16].

- **Causal Graph Dynamics**

  Causal Graph Dynamics [30] extend Cellular Automata to arbitrary, bounded-degree, time-varying graphs. The whole graph evolves in discrete time steps, and this global evolution is required to have a number of physics-like symmetries: shift-invariance (it acts everywhere the same) and causality (information has a bounded speed of propagation). We add a further physics-like symmetry, namely reversibility. This result has been presented at RC 2016 [15].

6.2. Implicit Computational Complexity

Participants: Emmanuel Hainry, Romain Péchoux.

We have written a full journal paper, accepted in Information and Computation (special issue of DICE 2015), on the complexity analysis of Object Oriented programming languages based on tiered types. The corresponding type system provides sound and complete characterization of the set of polynomial time computable functions. As a consequence, the heap-space and the stack-space requirements of typed programs are also bounded polynomially. This type system is inspired by previous works on Implicit Computational Complexity, using tiering and non-interference techniques. The presented methodology has several advantages. First, it provides explicit big O polynomial upper bounds to the programmer, hence its use could allow the programmer to avoid memory errors. Second, type checking is decidable in polynomial time. Last, it has a good expressivity since it analyzes most object oriented features like inheritance, overload, override and recursion. Moreover it can deal with loops guarded by objects and can also be extended to statements that alter the control flow like break or return.

6.3. Computing with Infinite Objects

Participant: Mathieu Hoyrup.

- **Decidable properties of subrecursive functions**

  We have studied the following problem : given a subrecursive class (like the primitive recursive functions, the polynomial-time computable functions, etc.) and a sound and complete programming language for that class, what are the properties of functions that are decidable (by a Turing machine), given a program for that function in the restricted language? We give a complete characterization of these properties. We show that they can be expressed as unions of elementary properties of being compressible. If $h : \mathbb{N} \to \mathbb{N}$ is a computable increasing unbounded function (like $\log(n)$ or 2^n), we say that a function $f : \mathbb{N} \to \mathbb{N}$ is h-compressible if for each n there is a program (in the restricted language) of size at most $h(n)$ computing a function that coincides with f on entries $0, 1, ..., n$. Whether f is h-compressible is decidable given a program for f, and every decidable property can be obtained as a combination of such elementary properties.

  We also prove that such a characterization does not hold for the whole class of total recursive functions, and leave the problem open for that class.

  The results appears in an article presented at ICALP 2016 [19].

- **Baire category and computability theory**

  Baire category is a very powerful tool in mathematical analysis to prove existence of objects with prescribed properties without having to explicitly build them, but showing instead that the class of objects with these properties is large in some sense. In Computability theory one often builds objects with very specific properties, notably to separate classes, and the proofs are often very involved. We show how Baire category can be adapted in order to be applied to computability theory, to prove existence results without the need of an explicit construction. We review notions that we introduced in the last years and provide new results in an invited paper at CiE 2016 [14].

6.4. Cellular automata as a model of computation

Participant: Nazim Fatès.

The density classification problem is a simple computational problem where a distributed system composed of many cells need to find the majority state in its initial configuration. It is known that no deterministic cellular automaton can solve this problem without making errors. On the other hand, it was shown that a probabilistic mixture of the traffic rule and the majority rule solves the one-dimensional problem correctly with a probability arbitrarily close to one. We investigated the possibility of a similar approach in two dimensions and introduced a companion problem, the particle spacing problem, as an intermediary step. We showed that although this second problem does not have a cellular automaton solution, the use of randomized frameworks, via interacting particle systems, could allow us to have interesting solutions, which were analysed with a theoretical approach and with numerical simulations [18].

In the same direction of research, we studied how to coordinate a team of agents to locate a hidden source on a two-dimensional discrete grid. The challenge here is to find the position of the source with only sporadic detections. This problem arises in various situations, for instance when insects emit pheromones to attract their partners. A search mechanism named infotaxis was previously proposed to explain how agents may progressively approach the source by using only intermittent detections.

We studied the problem of doing a collective infotaxis search with agents that are almost memoryless. We presented a bio-inspired model which mixes stochastic cellular automata and reactive multi-agent systems. The model, inspired by the behaviour of the social amoeba *Dictyostelium discoideum*, relies on the use of reaction-diffusion waves to guide the agents to the source. The random emissions of waves allows the formation of a group of amoebae, which successively act as emitters of waves or listeners, according to their local perceptions. Our worked showed that the model is worth considering and may provide a simple solution to coordinate a team to perform a distributed form of infotaxis [17].

7. Partnerships and Cooperations

7.1. National Initiatives

We participate in a PEPS project “Jeux quantiques sans probabilite´s”. The partners are Mehdi Mhalla (CR CNRS, LIG, coordinator), Pablo Arrighi (Prof. Aix-Marseille), Paul Dorbec (MdC, U. Bordeaux), Frédéric Magniez (DR CNRS, IRIF), Simon Perdrix (CR CNRS, CARTE).

7.1.1. ANR

- The team is a funding partner in ANR Elica (2014-2019), "Elargir les idées logistiques pour l’analyse de complexité". The CARTE team is well-known for its expertise in implicit computational complexity.

7.2. European Initiatives

7.2.1. FP7 & H2020 Projects

Mathieu Hoyrup participates in the Marie-Curie RISE project *Computing with Infinite Data* coordinated by Dieter Spreen (Univ. Siegen) that has been accepted and will start in April 2017.

7.3. International Initiatives

7.3.1. Participation in Other International Programs

- An Hubert Curien Partnership (PHC) PHC Imhotep from the French Ministry of Foreign Affairs and with the support of the French Ministry of National Education and Ministry of Higher Education and Research holds between members of EPC CARTE and Alexandria E-Just University.

- Foundations of Quantum Computation: Syntax and Semantics (FoQCoSS), Regional Program STIC-AmSud. This 2-year project has been accepted in late 2015. The Argentinian-Brazilian-French consortium consists of: Pablo ARRIGHI (Université Aix-Marseille, France), Alejandro DIAZ-CARO (Universidad Nacional de Quilmes, Argentina), Gilles DOWEK (Inria, France), Juliana KAIZER VIZZOTTO (Universidade Federal de Santa Maria, Brazil), Simon PERDRIX (CNRS/CARTE, France) and Benoît VALIRON (CentraleSupélec – LRI, France). The ultimate goal of this project is to study the foundations of quantum programming languages and related formalisms. With this goal in mind, we will need to study topics such as parallelism, probabilistic systems, isomorphisms, etc., which constitute subjects of study by themselves. The interest goes beyond having a working programming language for quantum computing; we are interested, on one hand, in its individual characteristics and its consequences for classical systems, and, on the other hand, in its implications for the foundations of quantum physics.

7.4. International Research Visitors

7.4.1. Visits of International Scientists

- Walid Gomaa, associate professor at Alexandria E-Just University, was invited during two months (March and May) in the team in the PHC Imhotep.

7.4.1.1. Internships

Arinta Auza (ENS Cachan / Indonesie)

7.4.2. Visits to International Teams

7.4.2.1. Research Stays Abroad

Nazim Fatès was invited for a short stay at the Technische Universtät Dresden, in the Centre for Information Services and High Performance Computing (ZIH), in the team of Andreas Deutsch, head of Department for Innovative Methods of Computing. He gave a talk at the monthly ZIH colloquium.

Simon Perdrix spent one month at the Simons Institute for Theoretical Computer Science at Berkeley, University of California, as an invited researcher during the semester of Logic and Computation (mid-November to Mid-December 2016)

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Events Organisation

8.1.1.1. General Chair, Scientific Chair

Nazim Fatès was a co-organiser of ACA'16 (Fourth International Workshop on Asynchronous Cellular Automata and Asynchronous Discrete Models), a workshop which was held during the ACRI 2016 conference, Fez (Morocco), September 8, 2016.

8.1.2. Scientific Events Selection

8.1.2.1. Member of the Conference Program Committees

- Nazim Fatès was member of the Program Committees of ANTS'16 (10th International Conference on Swarm Intelligence), AUTOMATA'16 (22nd International Workshop on Cellular Automata and Discrete Complex Systems) and ACRI'16 (12th International conference on Cellular Automata for Research and Industry).
- Emmanuel Hainry was member of the Program Committee of Developments in Implicit Computational Complexity (DICE) 2016.
- Mathieu Hoyrup was member of the Program Committee of Computability and Complexity in Analysis (CCA) 2016.
- Romain Péchoux was member of the Program Committee of Ressource Aware Computation (RAC) 2016.
- Simon Perdrix was member of the Program Committees of QPL'16 Quantum Physics and Logic, and IQFA'16 7th IQFA's Colloquium.

8.1.2.2. Reviewer

- Emmanuel Hainry reviewed articles for DICE and ICALP.
- Mathieu Hoyrup reviewed articles for ICALP and STACS.
- Emmanuel Jeandel reviewed articles for STACS and MFCS.
- Romain Péchoux reviewed articles for FOSSACS, ISMVL, RAC, LFA and STACS

8.1.3. Journal

8.1.3.1. Member of the Editorial Boards

- Nazim Fatès is a member of the editorial board of the *Journal of cellular automata*.
- Emmanuel Jeandel is member of the editorial board of RAIRO-ITA

8.1.3.2. Reviewer - Reviewing Activities

- Nazim Fatès reviewed articles for *Natural Computing*, the *Journal of statistical physics*, *Advanced in Complex systems*, the *Journal of cellular automata*.
- Emmanuel Hainry reviewed an article for Applicable Analysis and Discrete Mathematics.
- Mathieu Hoyrup reviewed articles for Bulletin of Symbolic Logic, Memoirs of the American Mathematical Society, Transactions of the American Mathematical Society.
- Emmanuel Jeandel reviewed articles for Advances in Mathematics, Journal of Discrete Algorithms and Ergodic Theory and Dynamical Systems.
- Romain Péchoux reviewed articles for AMS Mathematical Review, Information & Computation.
- Simon Perdrix reviewed articles for Quantum Information and Computation.

8.1.4. Invited Talks

- Mathieu Hoyrup was invited to give a talk in the special session "Constructive and computable analysis" of the conference Computability in Europe (CiE) in Paris, June 2016.
- Emmanuel Jeandel gave a talk for the national days of GDR-IM.

8.1.5. Leadership within the Scientific Community

- Nazim Fatès is the vice-chair of the IFIP working group 1.05 on Cellular Automata and Discrete Complex Systems.
- Simon Perdrix co-organised the quantum software workshop during the one-day event on quantum Technologies at the french Ministry of Research (July 5, 2016).

8.1.6. Scientific Expertise

- Emmanuel Jeandel reviewed projects for Agence Nationale de la Recherche

8.1.7. Research Administration

Isabelle Gnaedig is:

- vice-leader of the team CARTE,
- member of the scientific mediation committee at Inria Nancy Grand-Est.

Emmanuel Hainry is:

- member of the CNU (Conseil National des Universités), Section 27.
- organizer of the CARTE Seminar.
- examiner for the admission exam of ENS and École Polytechnique.

Mathieu Hoyrup is:

- principal investigator of a PHC Imhotep with Walid Gomaa (Alexandria E-Just University).
- organizer of the Formal Methods Seminar at Loria.

Simon Perdrix:

- is responsible of GT IQ (groupe de travail Informatique quantique) at the CNRS GdR IM (groupe de recherche Informatique Mathématique).
- has been elected member and scientific secretary at CoNRS (Comité National de la Recherche Scientifique) section 6.

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

Licence:

- Isabelle Gnaedig
  - To the limits of the computable, 6 hours, Opening course-conference of the collegium "Lorraine INP", Nancy France
- Emmanuel Hainry
  - Systèmes d'exploitation, 30h, L1, IUT Nancy Brabois, Université de Lorraine, France
  - Algorithmique, 40h, L1, IUT Nancy Brabois, Université de Lorraine, France
  - Web dynamique, 60h, L1, IUT Nancy Brabois, Université de Lorraine, France
  - Bases de données, 30h, L1, IUT Nancy Brabois, Université de Lorraine, France
  - Programmation objet, 12h, L2, IUT Nancy Braboi, Université de Lorraine, Frances
  - Complexité, 30h, L2, IUT Nancy Brabois, Université de Lorraine, France
- Mathieu Hoyrup
  - Bases de la Programmation Orientée Objet, 20 HETD, L2, Université de Lorraine, France
  - Interfaces Graphiques, 10 HETD, L2, Université de Lorraine, France
- Emmanuel Jeandel
  - Algorithmics and Programming 1, 60h, L1 Maths-Info
  - Algorithmics and Programming 4, 30h, L3 Informatique
  - Modelling Using Graph Theory, 30h, L3 Informatique
  - Networking, 15h, L3 Informatique
  - Data Compression, 45h, L2 Informatique
- Romain Péchoux
  - Programmation orientée objet, 61,5h, L3 MIASHS
  - Programmation orientée objet, 53,5h, L2 MIASHS
  - Outils logiques pour l'informatique, 35h, L1 MIASHS
  - Bases de données, 40h, L3 Sciences de la Gestion

  - Algorithmic complexity, 30h, L3 MIAGE, IGA Casablanca, Morocco.

Master:

- Nazim Fatès
  - Systèmes complexes adaptatifs, 15h ETD, M2, UL, France.
  - Agents intelligents et collectifs, 22h ETD, M1, UL, France.
- Isabelle Gnaedig
  - Design of Safe Software, Coordination of the module, M2, Telecom-Nancy (Université de Lorraine), Nancy, France,
  - Rule-based Programming, 20 hours, M2, Telecom-Nancy (Université de Lorraine), Nancy, France.
- Emmanuel Hainry
  - Complexity and Complex Systems, 12h, M2, FST, Université de Lorraine, France
- Emmanuel Jeandel
  - Algorithmics and Complexity, 30h, M1 Informatique
  - Combinatorial Optimization, 36h, M1 Informatique
- Romain Péchoux
  - Mathematics for computer science, 30h, M1 SCA
  - Advanced Java, 52,5h, M1 MIAGE
  - Implicit Complexity, 15h, M2 Informatique
- Simon Perfrix
  - Pépites Algorithmiques, 6h, M1/M2 at Ecole des Mines de Nancy.

8.2.2. Supervision

- Emmanuel Jeandel and Simon Perdrix supervised the Master Thesis of Renaud Vilmart on ZX-calculs, and the Master Thesis of Arinta Auza-Primandini on quantum circuits with memory.
- Emmanuel Jeandel and Simon Perdrix are advisors of Renaud Vilmart, PhD student (UL) since October 2016.
- Romain Péchoux is coadvisor of Pierre Mercuriali, PhD student, Université de Lorraine (50%, advisor: Miguel Couceiro, PR, Université de Lorraine).

8.2.3. Juries

- Mathieu Hoyrup participated in the jury of the PhD of Ludovic Patey, Université Paris Diderot, February 26.
- Emmanuel Jeandel reviewed the PhD thesis of Rodrigo Torres (Universidad de Concepción, Chile) in January, and participated in the PhD defense of Benoît Chappet de Vangel, Université de Lorraine, November 14th.

8.3. Popularization

Nazim Fatès contributed to the collective book *Lettres à Turing* (ed. Thierry Marchaisse, May 2016), which addresses the legacy of Turing in our Modern Times. He was invited to discuss this book and the question of artificial intelligence in three national radio programs:

- France Culture, La marche des sciences, “Cher alan Turing”, 1 hour, with Aurélie Luneau, 23 June 2016.
- RFI, Autour de la question, “Que devons-nous à Alan Turing?”, 1 hour, with Sophie Joubert, 24 June 2016.
- RFI, Autour de la question, “Jusqu’où ira l’intelligence artificielle?”, 1 hour, with Sophie Joubert, 7 October 2016.

Nazim Fatès participated to an open discussion (table ronde) on the theme of artificial intelligence (“Intelligence artificielle : quel monde prépare-t-elle ?”), invitation by the Cercle universitaire of Enghien-les-bains, on the 27th of Septembre in Enghien-les-bains. He was interviewed by Eric Chaverou, journalist at France Culture for his radio program of May 20, 2016, on the theme: “L’intelligence artificielle made in France”. This interview is available on the website of the radio program or directly via soundcloud. He participated to a public debate on the theme “Jusqu’où ira l’intelligence artificielle ?” the Café des sciences et techniques, organised by the CNAM, in Épinal, 21 January 2016.

9. Bibliography

Major publications by the team in recent years

[1] O. BOURNEZ, D. GRAÇA, E. HAINRY. *Computation with perturbed dynamical systems*, in "Journal of Computer and System Sciences", August 2013, vol. 79, n^{o} 5, p. 714-724 [*DOI :* 10.1016/J.JCSS.2013.01.025], http://hal.inria.fr/hal-00861041.

[2] N. FATÈS, I. MARCOVICI, S. TAATI. *Two-dimensional traffic rules and the density classification problem*, in "International Workshop on Cellular Automata and Discrete Complex Systems, AUTOMATA 2016", Zürich, France, Lecture Notes of Computer Science, June 2016, vol. 9664 [*DOI :* 10.1007/978-3-319-39300-1_11], https://hal.inria.fr/hal-01290290.

[3] H. FÉRÉE, E. HAINRY, M. HOYRUP, R. PÉCHOUX. *Characterizing polynomial time complexity of stream programs using interpretations*, in "Journal of Theoretical Computer Science (TCS)", January 2015, vol. 585, p. 41-54 [*DOI :* 10.1016/J.TCS.2015.03.008], https://hal.inria.fr/hal-01112160.

[4] I. GNAEDIG, H. KIRCHNER. *Proving Weak Properties of Rewriting*, in "Theoretical Computer Science", 2011, vol. 412, p. 4405-4438 [*DOI :* 10.1016/J.TCS.2011.04.028], http://hal.inria.fr/inria-00592271/en.

[5] E. HAINRY, R. PÉCHOUX. *Objects in Polynomial Time*, in "APLAS 2015", Pohang, South Korea, X. FENG, S. PARK (editors), Lecture Notes in Computer Science, Springer, November 2015, vol. 9458, p. 387–404 [*DOI :* 10.1007/978-3-319-26529-2_21], https://hal.inria.fr/hal-01206161.

[6] M. HOYRUP. *The decidable properties of subrecursive functions*, in "International Colloquium on Automata, Languages, and Programming (ICALP) 2016", Rome, Italy, 43rd International Colloquium on Automata, Languages, and Programming, ICALP 2016, July 12-15, 2016, Rome, Italy, July 2016 [*DOI :* 10.4230/LIPICS.ICALP.2016.108], https://hal.inria.fr/hal-01308224.

[7] M. HOYRUP, C. ROJAS. *On the information carried by programs about the objects they compute*, in "STACS15", Munich, Germany, March 2015, https://hal.inria.fr/hal-01067618.

[8] E. JEANDEL. *Computability of the entropy of one-tape Turing Machines*, in "STACS - Symposium on Theoretical Aspects of Computer Science", Lyon, France, E. MAYR, N. PORTIER (editors), LIPCS, March 2014, vol. 25, p. 421-432, First version [*DOI :* 10.4230/LIPICS.STACS.2014.421], https://hal.inria.fr/hal-00785232.

[9] E. JEANDEL, P. VANIER. *Hardness of Conjugacy, Embedding and Factorization of multidimensional Subshifts of Finite Type*, in "STACS - 30th International Symposium on Theoretical Aspects of Computer Science", Kiel, Germany, N. PORTIER, T. WILKE (editors), Leibniz International Proceedings in Informatics (LIPIcs), Schloss Dagstuhl–Leibniz-Zentrum fuer Informatik, February 2013, vol. 20, p. 490–501 [*DOI :* 10.4230/LIPICS.STACS.2013.490], http://hal.inria.fr/hal-00840384.

[10] S. PERDRIX, Q. WANG.*Supplementarity is Necessary for Quantum Diagram Reasoning* *, in "41st International Symposium on Mathematical Foundations of Computer Science (MFCS 2016)", Krakow, Poland, Leibniz International Proceedings in Informatics (LIPIcs), August 2016, vol. 58, p. 76:1–76:14 [*DOI :* 10.4230/LIPICS.MFCS.2016.76], https://hal.archives-ouvertes.fr/hal-01361419.

Publications of the year

Articles in International Peer-Reviewed Journal

[11] G. BONFANTE, R. KAHLE, J.-Y. MARION, I. OITAVEM.*Two function algebras defining functions in NC k boolean circuits*, in "Journal of Information and Computation", 2016, accepté à Information and Computation, https://hal.inria.fr/hal-01113342.

[12] M. HOYRUP.*Genericity of weakly computable objects*, in "Theory of Computing Systems", December 2016 [*DOI :* 10.1007/S00224-016-9737-6], https://hal.inria.fr/hal-01095864.

[13] M. HOYRUP, C. ROJAS.*On the Information Carried by Programs About the Objects they Compute*, in "Theory of Computing Systems", December 2016 [*DOI :* 10.1007/S00224-016-9726-9], https://hal.inria.fr/hal-01413066.

Invited Conferences

[14] M. HOYRUP.*The Typical Constructible Object*, in "Computability In Europe", Paris, France, June 2016, p. 115 - 123 [*DOI :* 10.1007/978-3-319-40189-8_12], https://hal.inria.fr/hal-01396167.

International Conferences with Proceedings

[15] P. ARRIGHI, S. MARTIEL, S. PERDRIX.*Reversible Causal Graph Dynamics*, in "Reversible Computation", Bologna, Italy, Lecture Notes in Computer Science, July 2016, vol. 9720, p. 73-88 [*DOI :* 10.1007/978-3-319-40578-0_5], https://hal.archives-ouvertes.fr/hal-01361427.

[16] M. BACKENS, S. PERDRIX, Q. WANG.*A Simplified Stabilizer ZX-calculus*, in "13th International Conference on Quantum Physics and Logic", Glasgow, United Kingdom, June 2016, 27 pages, https://hal.inria.fr/hal-01404591.

[17] N. FATÈS.*Collective infotaxis with reactive amoebae: a note on a simple bio-inspired mechanism*, in "12th International Conference on Cellular Automata for Research and Industry, ACRI 2016", Fez, Morocco, Lecture Notes of Computer Science, Springer, September 2016, vol. 9863 [*DOI :* 10.1007/978-3-319-44365-2_15], https://hal.inria.fr/hal-01327983.

[18] N. FATÈS, I. MARCOVICI, S. TAATI.*Two-dimensional traffic rules and the density classification problem*, in "International Workshop on Cellular Automata and Discrete Complex Systems, AUTOMATA 2016", Zürich, France, Lecture Notes of Computer Science, June 2016, vol. 9664 [*DOI :* 10.1007/978-3-319-39300-1_11], https://hal.inria.fr/hal-01290290.

[19] M. HOYRUP.*The decidable properties of subrecursive functions*, in "International Colloquium on Automata, Languages, and Programming (ICALP) 2016", Rome, Italy, 43rd International Colloquium on Automata, Languages, and Programming, ICALP 2016, July 12-15, 2016, Rome, Italy, July 2016 [*DOI :* 10.4230/LIPICS.ICALP.2016.108], https://hal.inria.fr/hal-01308224.

[20] S. PERDRIX, Q. WANG.*Supplementarity is Necessary for Quantum Diagram Reasoning **, in "41st International Symposium on Mathematical Foundations of Computer Science (MFCS 2016)", Krakow, Poland, Leibniz International Proceedings in Informatics (LIPIcs), August 2016, vol. 58, p. 76:1–76:14 [*DOI :* 10.4230/LIPICS.MFCS.2016.76], https://hal.archives-ouvertes.fr/hal-01361419.

Scientific Books (or Scientific Book chapters)

[21] N. FATÈS.*Aesthetics and randomness in cellular automata*, in "Designing Beauty: The Art of Cellular Automata", A. ADAMATZKY, G. J. MARTÍNEZ (editors), Emergence, Complexity and Computation, Springer, 2016 [*DOI :* 10.1007/978-3-319-27270-2_23], https://hal.inria.fr/hal-01256384.

Scientific Popularization

[22] N. FATÈS.*Lettres à Turing : contribution de Nazim Fatès (lettre de Socrate à Turing): Théoreo ! Je vois !*, in "Lettres à Turing", ed. Thierry Marchaisse, May 2016, Livre à paraître aux éditions Thierry Marchaisse, sous la direction de Jean-Marc Lévy-Leblond ; parution prévue le 5 mai 2016, https://hal.inria.fr/hal-01253263.

Other Publications

[23] N. FATÈS, V. CHEVRIER, O. BOURÉ.*Is there a trade-off between simplicity and robustness? Illustration on a lattice-gas model of swarming*, February 2016, forthcoming, https://hal.inria.fr/hal-01230145.

[24] H. GODFROY, J.-Y. MARION.*A theory of reflexive computation based on soft intuitionistic logic*, October 2016, working paper or preprint, https://hal.inria.fr/hal-01394263.

[25] H. GODFROY, J.-Y. MARION.*Abstract Self Modifying Machines*, November 2016, working paper or preprint, https://hal.inria.fr/hal-01390838.

[26] P. HOYER, M. MHALLA, S. PERDRIX.*Contextuality in multipartie pseudo-telepathy graph games*, October 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01378413.

[27] E. JEANDEL.*Aperiodic Subshifts on Polycyclic Groups*, August 2016, Previous version had a mistake in the proof of the polycyclic case. The new proof needs a very strong new result by Barbieri and Sablik, that the authors hopes is avoidable, https://hal.inria.fr/hal-01213364.

[28] S. PERDRIX, L. SANSELME.*Determinism and Computational Power of Real Measurement-based Quantum Computation*, October 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01377339.

References in notes

[29] L. ADLEMAN.*An Abstract Theory of Computer Viruses*, in "Advances in Cryptology — CRYPTO'88", Lecture Notes in Computer Science, 1988, vol. 403.

[30] P. ARRIGHI, G. DOWEK.*Causal graph dynamics*, in "Proceedings of ICALP 2012, Warwick", Springer, July 2012, vol. 7392, p. 54–66.

[31] E. ASARIN, O. MALER, A. PNUELI.*Reachability analysis of dynamical systems having piecewise-constant derivatives*, in "Theoretical Computer Science", February 1995, vol. 138, n^{o} 1, p. 35–65.

[32] F. BAADER, T. NIPKOW.*Term rewriting and all that*, Cambridge University Press, New York, NY, USA, 1998.

[33] M. BACKENS.*The ZX-calculus is complete for stabilizer quantum mechanics*, in "New Journal of Physics", 2014, vol. 16, 093021.

[34] P. BEAUCAMPS, I. GNAEDIG, J.-Y. MARION.*Behavior Abstraction in Malware Analysis*, in "1st International Conference on Runtime Verification", St. Julians, Malte, G. ROSU, O. SOKOLSKY (editors), Lecture Notes in Computer Science, Springer-Verlag, August 2010, vol. 6418, p. 168-182, http://hal.inria.fr/inria-00536500/en/.

[35] P. BEAUCAMPS, I. GNAEDIG, J.-Y. MARION.*Abstraction-based Malware Analysis Using Rewriting and Model Checking*, in "ESORICS", Pisa, Italie, S. FORESTI, M. YUNG (editors), LNCS, Springer, 2012, vol. 7459, p. 806-823 [*DOI :* 10.1007/978-3-642-33167-1], http://hal.inria.fr/hal-00762252.

[36] P. BELL, J.-C. DELVENNE, R. JUNGERS, V. D. BLONDEL.*The Continuous Skolem-Pisot Problem: On the Complexity of Reachability for Linear Ordinary Differential Equations*, 2008, http://arxiv.org/abs/0809.2189.

[37] L. BLUM, M. SHUB, S. SMALE.*On a theory of computation and complexity over the real numbers; NP completeness, recursive functions and universal machines*, in "Bulletin of the American Mathematical Society", July 1989, vol. 21, n^{o} 1, p. 1–46.

[38] G. BONFANTE, M. KACZMAREK, J.-Y. MARION.*On abstract computer virology: from a recursion-theoretic perspective*, in "Journal in Computer Virology", 2006, vol. 1, n^{o} 3-4.

[39] M.G.J. VAN DEN. BRAND, A. VAN. DEURSEN, J. HEERING, H.A. DE JONG, M. DE JONGE, T. KUIPERS, P. KLINT, L. MOONEN, P. OLIVIER, J. SCHEERDER, J. VINJU, E. VISSER, J. VISSER.*The ASF+SDF Meta-Environment: a Component-Based Language Development Environment*, in "Compiler Construction (CC '01)", R. WILHELM (editor), Lecture Notes in Computer Science, Springer, 2001, vol. 2027, p. 365–370.

[40] M. S. BRANICKY.*Universal computation and other capabilities of hybrid and continuous dynamical systems*, in "Theoretical Computer Science", 6 February 1995, vol. 138, n^{o} 1, p. 67–100.

[41] M. CLAVEL, F. DURÁN, S. EKER, P. LINCOLN, N. MARTÍ-OLIET, J. MESEGUER, C. TALCOTT.*The Maude 2.0 System*, in "Proceedings of the 14th International Conference on Rewriting Techniques and Applications", R. NIEUWENHUIS (editor), Lecture Notes in Computer Science, Springer, June 2003, vol. 2706, p. 76-87.

[42] F. COHEN.*Computer Viruses*, University of Southern California, January 1986.

[43] H. COMON.*Inductionless Induction*, in "Handbook of Automated Reasoning", A. ROBINSON, A. VORONKOV (editors), Elsevier Science, 2001, vol. I, chap. 14, p. 913-962.

[44] N. DERSHOWITZ, D. PLAISTED.*Rewriting*, in "Handbook of Automated Reasoning", A. ROBINSON, A. VORONKOV (editors), Elsevier Science, 2001, vol. I, chap. 9, p. 535-610.

[45] A. EDALAT, P. SÜNDERHAUF.*A domain-theoretic approach to computability on the real line*, in "Theoretical Computer Science", 1999, vol. 210, n^{o} 1, p. 73–98.

[46] E. FILIOL.*Computer Viruses: from Theory to Applications*, Springer-Verlag, 2005.

[47] E. FILIOL.*Malware Pattern Scanning Schemes Secure Against Black-box Analysis*, in "Journal in Computer Virology", 2006, vol. 2, n^{o} 1, p. 35-50.

[48] E. FILIOL.*Techniques virales avancées*, Springer, 2007.

[49] E. FILIOL, G. JACOB, M. LE LIARD.*Evaluation methodology and theoretical model for antiviral behavioural detection strategies*, in "Journal in Computer Virology", 2007, vol. 3, n^{o} 1, p. 23-37.

[50] O. FISSORE, I. GNAEDIG, H. KIRCHNER.*Termination of rewriting with local strategies*, in "Selected papers of the 4th International Workshop on Strategies in Automated Deduction", M. P. BONACINA, B. GRAMLICH (editors), Electronic Notes in Theoretical Computer Science, Elsevier Science Publishers, 2001, vol. 58.

[51] O. FISSORE, I. GNAEDIG, H. KIRCHNER.*CARIBOO : An induction based proof tool for termination with strategies*, in "Proceedings of the Fourth International Conference on Principles and Practice of Declarative Programming", Pittsburgh (USA), ACM Press, October 2002, p. 62–73.

[52] O. FISSORE, I. GNAEDIG, H. KIRCHNER.*Outermost ground termination*, in "Proceedings of the Fourth International Workshop on Rewriting Logic and Its Applications", Pisa, Italy, Electronic Notes in Theoretical Computer Science, Elsevier Science Publishers, September 2002, vol. 71.

[53] O. FISSORE, I. GNAEDIG, H. KIRCHNER.*A proof of weak termination providing the right way to terminate*, in "First International Colloquium on Theoretical Aspect of Computing", Guiyang, China, Lecture Notes in Computer Science, Springer, September 2004, vol. 3407, p. 356-371.

[54] I. GNAEDIG, H. KIRCHNER.*Computing Constructor Forms with Non Terminating Rewrite Programs*, in "Proceedings of the Eighth ACM-SIGPLAN International Symposium on Principles and Practice of Declarative Programming", Venice, Italy, ACM Press, July 2006, p. 121–132.

[55] I. GNAEDIG, H. KIRCHNER.*Termination of Rewriting under Strategies*, in "ACM Transactions on Computational Logic", 2009, vol. 10, n^{o} 2, p. 1-52, http://hal.inria.fr/inria-00182432/en/.

[56] I. GNAEDIG.*Induction for Positive Almost Sure Termination*, in "Proceedings of the 9th ACM-SIGPLAN International Symposium on Principles and Practice of Declarative Programming - PPDP 2007", Wroclaw, Pologne, ACM, 2007, p. 167-177, http://hal.inria.fr/inria-00182435/en/.

[57] I. GNAEDIG, H. KIRCHNER.*Narrowing, Abstraction and Constraints for Proving Properties of Reduction Relations*, in "Rewriting, Computation and Proof - Essays Dedicated to Jean-Pierre Jouannaud on the Occasion of His 60th Birthday", Paris, France, H. COMON, C. KIRCHNER, H. KIRCHNER (editors), Lecture Notes in Computer Science, Springer, 2007, vol. 4600, p. 44-67, http://hal.inria.fr/inria-00182434/en/.

[58] E. HAINRY.*Computing omega-limit Sets in Linear Dynamical Systems*, in "Unconventional Computation", Autriche Vienne, C. S. CALUDE, J. F. COSTA, R. FREUND, M. OSWALD, G. ROZENBERG (editors), Springer, 2008, vol. 5204, p. 83–95, http://hal.inria.fr/inria-00250111/en/.

[59] E. HAINRY.*Reachability in linear dynamical systems*, in "Computability in Europe Logic and Theory of Algorithms", Grèce Athènes, A. BECKMANN, C. DIMITRACOPOULOS, B. LÖWE (editors), Springer, 2008, vol. 5028, p. 241-250, http://hal.inria.fr/inria-00202674/en/.

[60] S. KLEENE.*Introduction to Metamathematics*, Van Nostrand, 1952.

[61] K.-I. KO.*Complexity Theory of Real Functions*, Birkhäuser, 1991.

[62] J.-Y. MARION.*Complexité implicite des calculs, de la théorie à la pratique*, Université Nancy 2, 2000, Habilitation à diriger les recherches.

[63] J.-Y. MARION, J.-Y. MOYEN.*Efficient first order functional program interpreter with time bound certifications*, in "Logic for Programming and Automated Reasoning, 7th International Conference, LPAR 2000, Reunion Island, France", M. PARIGOT, A. VORONKOV (editors), Lecture Notes in Computer Science, Springer, Nov 2000, vol. 1955, p. 25–42.

[64] J.-Y. MARION, R. PÉCHOUX.*Resource Analysis by Sup-interpretation*, in "FLOPS", Lecture Notes in Computer Science, Springer, 2006, vol. 3945, p. 163–176.

[65] C. MOORE.*Recursion Theory on the Reals and Continuous-Time Computation*, in "Theor. Comput. Sci.", 1996, vol. 162, n^{o} 1, p. 23-44.

[66] P.-E. MOREAU, C. RINGEISSEN, M. VITTEK.*A Pattern Matching Compiler for Multiple Target Languages*, in "12th Conference on Compiler Construction, Warsaw (Poland)", G. HEDIN (editor), LNCS, Springer-Verlag, May 2003, vol. 2622, p. 61–76, http://www.loria.fr/~moreau/Papers/MoreauRV-CC2003.ps.gz.

[67] B. MORIN, L. MÉ.*Intrusion detection and virology: an analysis of differences, similarities and complementariness*, in "Journal in Computer Virology", 2007, vol. 3, n^{o} 1, p. 33-49.

[68] P. ORPONEN.*A Survey of Continuous-Time Computation Theory*, in "Advances in Algorithms, Languages, and Complexity", D.-Z. DU, K.-I. KO (editors), Kluwer Academic Publishers, 1997, p. 209-224, http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.53.1991.

[69] C. E. SHANNON.*Mathematical Theory of the Differential Analyser*, in "Journal of Mathematics and Physics MIT", 1941, vol. 20, p. 337-354.

[70] TERESE.*Term Rewriting Systems*, Cambridge Tracts in Theoretical Computer Science, Cambridge University Press, 2003, n^{o} 55.

[71] K. THOMPSON.*Reflections on Trusting Trust*, in "Communication of the ACM", august 1984, vol. 27, p. 761–763, Also appears in ACM Turing Award Lectures: The First Twenty Years 1965-1985.

[72] M. WEBSTER, G. MALCOLM.*Detection of metamorphic computer viruses using algebraic specification*, in "Journal in Computer Virology", 2006, vol. 2, n^{o} 3, p. 149-161.

[73] M. WEBSTER, G. MALCOLM.*Detection of metamorphic and virtualization-based malware using algebraic specification*, in "Journal in Computer Virology", 2009, vol. 5, n^{o} 3, p. 221-245.

[74] K. WEIHRAUCH.*Computable Analysis*, Springer, 2000.

[75] C. S. DE WITT, V. ZAMDZHIEV.*The ZX-calculus is incomplete for quantum mechanics*, in "EPTCS", 2014, vol. 172, p. 285–292, 10.4204/EPTCS.172.20.2014.

[76] J. VON NEUMANN.*Theory of Self-Reproducing Automata*, University of Illinois Press, Urbana, Illinois, 1966, edited and completed by A.W.Burks.

Project-Team COAST

Web Scale Trustworthy Collaborative Service Systems

IN COLLABORATION WITH: Laboratoire lorrain de recherche en informatique et ses applications (LORIA)

IN PARTNERSHIP WITH:
CNRS

Université de Lorraine

RESEARCH CENTER
Nancy - Grand Est

THEME
Distributed Systems and middleware

Table of contents

Project-Team COAST

Creation of the Team: 2014 July 01, updated into Project-Team: 2015 July 01

Keywords:

Computer Science and Digital Science:

1.1.6. - Cloud
1.1.7. - Peer to peer
1.3. - Distributed Systems
2.5.1. - Software Architecture & Design
2.6.2. - Middleware
3.1.3. - Distributed data
3.1.5. - Control access, privacy
5.1.1. - Engineering of interactive systems
5.1.2. - Evaluation of interactive systems
7.1. - Parallel and distributed algorithms

Other Research Topics and Application Domains:

6.1.1. - Software engineering
6.3.1. - Web
6.5. - Information systems
8.4. - Security and personal assistance
8.4.1. - Crisis management
9.1.1. - E-learning, MOOC
9.5.1. - Psychology
9.6. - Reproducibility
9.8. - Privacy

1. Members

Research Scientist

Claudia-Lavinia Ignat [Inria, Researcher]

Faculty Members

François Charoy [Team leader, Univ. Lorraine, Professor, HDR]
Khalid Benali [Univ. Lorraine, Associate Professor, HDR]
Gérôme Canals [Univ. Lorraine, Associate Professor]
Claude Godart [Univ. Lorraine, Professor]
Gérald Oster [Univ. Lorraine, Associate Professor]
Olivier Perrin [Univ. Lorraine, Professor, HDR]
Pascal Urso [Univ. Lorraine, Associate Professor]
Samir Youcef [Univ. Lorraine, Associate Professor]

Technical Staff

Jean-Philippe Eisenbarth [Univ. Lorraine, from Nov 2016]
Phillippe Kalitine [Univ. Lorraine]
Matthieu Nicolas [Inria]

PhD Students

Amina Ahmed Nacer [Univ. Bejaia]
Ahmed Bouchami [Univ. Lorraine, until Aug 2016]
Quang Vinh Dang [Univ. Lorraine]
Victorien Elvinger [Univ. Lorraine]
Elio Goettelmann [CRP Henri Tudor, until Jan 2016]
Abir Ismaili-Alaoui [Univ. Lorraine, from Sep 2016]
Quentin Laporte Chabasse [Univ. Lorraine, from Oct 2016]
Jordi Martori Adrian [Inria]
Hoai Le Nguyen [Univ. Lorraine]
Hoang Long Nguyen [Univ. Lorraine]
Guillaume Rosinosky [Bonitasoft, granted by CIFRE]

Post-Doctoral Fellows

Mohammed Riyadh Abdmeziem [Univ. Lorraine, from Oct 2016]
Kahina Bessai Ep. Youcef [Univ. Lorraine,]

Administrative Assistants

Sophie Drouot [Inria]
Delphine Hubert [Univ. Lorraine]
Martine Kuhlmann [CNRS]

Others

Luc André [Univ. Lorraine, until May 2016]
Marc Delpech [Univ. Lorraine, Internship, from Jun 2016 until Aug 2016]
Thomas Le Saux [Univ. Lorraine, Internship, from Jun 2016 until Aug 2016]
Bruno Sinteff [Inria, Internship, from May 2016 until Jul 2016]

2. Overall Objectives

2.1. Overall Objectives

The advent of the Cloud, of smart mobile devices and of service-based architecture has opened a field of possibilities wide as the invention of the Web 25 years ago. Software companies now deliver applications and services using the Web as a platform. From text to video editing, from data analytics to process management, they distribute business applications to users within their web browser or on some mobile appliance [0]. These services are deployed on sophisticated infrastructures that can cope with very demanding loads. The Software as a Service approach (SaaS) highlights their cooperative nature, by enabling the storage of data in cloud infrastructures that can be easily shared among users. Thus, clients consume applications through service API (web services), available on delivery platforms, called stores or markets. This approach of the distribution of software outstrips the traditional software distribution channels, in both scale and opportunity. Scale has different dimensions : the number of users (communities rather than groups), the size of data produced and managed (billions of documents), the number of services and of organizations (tens of thousands). Opportunity refers to the infinite number of combinations between these services and the many ways to consume and use them.

This fast-paced evolution challenges research because the creation of applications from the composition of services must incorporate new content and context based constraints. From a socio-technical perspective, the behaviour of users is evolving constantly as they get acculturated to new services and ways to cooperate. Mere enhancement of current existing solutions to cope with these challenges is likely insufficient. We conduct a dedicated research effort to tackle the problems arising from the evolution of contemporary technologies and of those we can anticipate.

[0] See http://blog.programmableweb.com/2011/09/16/open-api-growth-a-visualization/

For this purpose, we explore three directions: large scale collaborative data management, data centred service composition and above all, a foundation for the construction of trustworthy collaborative systems.

Large scale collaborative data management concerns mostly the problem of allowing people to collaborate on shared data, synchronously or not, on a central server or on a peer to peer network. Although this research has a long history referring back to [24], new challenges arise regarding needs that are occurring with the acculturation of users to collaboration like the number of participants to a collaboration (a crowd), sharing among different organisations and the nature of documents that are shared and produced. The problem here is to design new algorithms and to evaluate them under different usage conditions and constraints and for different kinds of data.

Data centred service composition deals with the challenge of creating applications by composing services from different providers. Service composition has been studied for some time now but the technical evolution and the growing availability of public API oblige us to reconsider the problem [23]. Our goal here is, taking into account this evolution, like the advent of the Cloud, the availability at a large scale of public API based on the REST [0] architectural style, to design models, methods and tools to help developers to compose these services in a safe and effective way.

Based on the work that we do in the two first topics, our main research direction aims at providing support to build **trustworthy collaborative applications** based on the knowledge that we can gather from the underlying algorithms, from the composition of services and from the quality of services that can be deduced and monitored. The complexity of the context in which applications are executed does not allow to provide proven guarantees. Our goal is to base our work on a contractual and monitored approach to provide users with confidence in the service they use. It is very surprising to see to what extent people rely today on services with very little knowledge about the amount of confidence they put in these services. As soon as these services are based on composition of other unknown services, it becomes very difficult to understand the consequences of the failure of a component of the composition for instance.

We follow a path that portrays a ruptured continuum, to underscore both the endurance of the common questions along with the challenge of accommodating a new scale. We regard collaborative systems as a combination of supportive services, encompassing safe data management and data sharing. Trustworthy data centred services are an essential support for collaboration at the scale of communities and organisations. We see there that we aim at combining our results and expertise to achieve a new leap forward toward the understanding and the mastering of methods and techniques that allow the engineering and the use of large scale collaborative systems.

3. Research Program

3.1. Introduction

Our scientific foundations are grounded on distributed collaborative systems supported by sophisticated data sharing mechanisms and on service oriented computing with an emphasis on orchestration and on non-functional properties.

Distributed collaborative systems enable distributed group work supported by computer technologies. Designing such systems requires an expertise in Distributed Systems and in Computer-supported collaborative Work research area. Besides theoretical and technical aspects of distributed systems, the design of distributed collaborative systems must take into account the human factor to offer solutions suitable for users and groups. The Coast team vision is to move away from a centralized authority based collaboration towards a decentralized collaboration where users have full control over their data that they can store locally and decide with whom to share them. The Coast team investigates the issues related to the management of distributed shared data and coordination between users and groups.

[0] representational state transfer

Service oriented Computing [26] is an established domain on which the ECOO, Score and now the Coast teams have been contributing for a long time. It refers to the general discipline that studies the development of computer applications on the web. A service is an independent software program with a specific functional context and capabilities published as a service contract (or more traditionally an API). A service composition aggregates a set of services and coordinates their interactions. The scale, the autonomy of services, the heterogeneity and some design principles underlying Service Oriented Computing open new research questions that are at the basis of our research. They span the disciplines of **distributed computing**, **software engineering** and **computer supported collaborative work** (CSCW). Our approach to contribute to the general vision of Service Oriented Computing and more generally to the emerging discipline of Service Science has been and is still to focus on the issue of the efficient and flexible construction of reliable and secure high level services through the coordination/orchestration/composition of other services provided by distributed organizations or people.

3.2. Consistency Models for Distributed Collaborative Systems

Collaborative systems are distributed systems that allow users to share data. One important issue is to manage consistency of shared data according to concurrent access. Traditional consistency criteria such as serializability, linearizability are not adequate for collaborative systems.

Causality, Convergence and Intention preservation (CCI) [30] are more suitable for developing middleware for collaborative applications.

We develop algorithms for ensuring CCI properties on collaborative distributed systems. Constraints on the algorithms are different according to the kind of distributed system and to the data structure. The distributed system can be centralized, decentralized or peer-to-peer. The type of data can include strings, growable arrays, ordered trees, semantic graphs and multimedia data.

3.3. Optimistic Replication

Replication of data among different nodes of a network allows improving reliability, fault-tolerance, and availability. When data are mutable, consistency among the different replicas must be ensured. Pessimistic replication is based on the principle of single-copy consistency while optimistic replication allows the replicas to diverge during a short time period. The consistency model for optimistic replication [28] is called eventual consistency, meaning that replicas are guaranteed to converge to the same value when the system is idle.

Our research focuses on the two most promising families of optimistic replication algorithms for ensuring CCI:

- the operational transformation (OT) algorithms [24]
- the algorithms based on commutative replicated data types (CRDT) [27].

Operational transformation algorithms are based on the application of a transformation function when a remote modification is integrated into the local document. Integration algorithms are generic, being parametrized by operational transformation functions which depend on replicated document types. The advantage of these algorithms is their genericity. These algorithms can be applied to any data type and they can merge heterogeneous data in a uniform manner.

Commutative replicated data types is a new class of algorithms initiated by WOOT [25] a first algorithm designed WithOut Operational Transformations. They ensure consistency of highly dynamic content on peer-to-peer networks. Unlike traditional optimistic replication algorithms, they can ensure consistency without concurrency control. CRDT algorithms rely on natively commutative operations defined on abstract data types such as lists or ordered trees. Thus, they do not require a merge algorithm or an integration procedure.

3.4. Process Orchestration and Management

Process Orchestration and Management is considered as a core discipline behind Service Management and Computing. It includes the analysis, the modelling, the execution, the monitoring and the continuous improvement of enterprise processes and is for us a central domain of studies.

Much efforts have been devoted in the past years to establish standard business process models founded on well grounded theories (e.g. Petri Nets) that meet the needs of both business analysts but also of software engineers and software integrators. This has lead to heated debate in the BPM community as the two points of view are very difficult to reconcile. On one side, the business people in general require models that are easy to use and understand and that can be quickly adapted to exceptional situations. On the other side, IT people need models with an operational semantic in order to be able transform them into executable artefacts. Part of our work has been an attempt to reconcile these point of views. It resulted in the development of the Bonita Business process management system and more recently on our work in crisis management where the same people are designing, executing and monitoring the process as it executes. But more generally, and at a larger scale, we have been considering the problem of processes spanning the barriers of organisations and thus more general problem of service composition as a way to coordinate inter organisational construction of applications providing value based on the composition of lower level services [22].

3.5. Service Composition

We are considering processes as pieces of software whose execution traverse the boundaries of organisations. This is especially true with service oriented computing where processes compose services produced by many organisations. We tackle this problem from very different perspectives, trying to find the best compromise between the need for privacy of internal processes from organisations and the necessity to publicize large part of them, proposing to distribute the execution and the orchestration of processes among the organisations themselves, and attempting to ensure non-functional properties in this distributed setting [21].

Non-functional aspects of service composition relate to all the properties and service agreements that one wants to ensure and that are orthogonal to the actual business but that are important when a service is selected and integrated in a composition. This includes transactional context, security, privacy, and quality of service in general. Defining and orchestrating services on a large scale while providing the stakeholders with some strong guarantees on their execution is a first class problem for us. For a long time, we have proposed models and solutions to ensure that some properties (e.g. transactional properties) were guaranteed on process execution, either through design or through the definition of some protocols. Our work has also been extended to the problems of security, privacy and service level agreement among partners. These questions are still central in our work. One major problem of current approaches is to monitor the execution of the compositions, integrating the distributed dimension. This problem can be tackled using event-based algorithms and techniques. Using our event oriented composition framework DISC, we have obtained new results dedicated to the runtime verification of violations in service choreographies.

4. New Software and Platforms

4.1. MUTE

Multi-User Text Editor
FUNCTIONAL DESCRIPTION

MUTE (Multi-User Text Editor) is a web-based text editing tool that allows users to edit documents collaboratively in real-time. It implements our recent work on collaborative editing algorithms and more specifically the LogootSplit+ approach. Compared to existing web-based collaborative text editing tool this editor does not require a powerful central server since the server is not performing any computation and acts as a simple broadcast server. Our editor offers support for working offline while still being able to reconnect at a later time.

- Participants: Gérald Oster, François Charoy, Claudia-Lavinia Ignat, Phillippe Kalitine, Matthieu Nicolas and Victorien Elvinger
- Contact: Gérald Oster
- URL: https://github.com/coast-team/mute/

4.2. NetFlux

Peer-to-Peer Network Library over WebRTC
FUNCTIONAL DESCRIPTION

NetFlux is a Nodejs library that allows users to deploy a peer-to-peer network between web browsers using the WebRTC technology.

- Participants: Gérald Oster, Phillippe Kalitine, Matthieu Nicolas.
- Contact: Gérald Oster
- URL: https://github.com/coast-team/netflux

4.3. MUTE-structs

Peer-to-Peer Network Library over WebRTC
FUNCTIONAL DESCRIPTION

MUTE-structs is a Nodejs module that provides an implementation of the LogootSplit CRDT algorithm. It is an optimistic replication algorithm that ensures eventual consistency on replicated text sequences. It is used in the MUTE real-time collaborative text editor.

- Participants: Gérald Oster, Claudia-Lavinia Ignat, Phillippe Kalitine, Matthieu Nicolas and Victorien Elvinger
- Contact: Gérald Oster
- URL: https://github.com/coast-team/mute-structs

4.4. Replication Benchmarker

FUNCTIONAL DESCRIPTION

The Replication Benchmarker is a performance evaluation framework for optimistic replication mechanisms used in collaborative applications. It contains a library of implementation of several CRDT (Commutative Replicated Data Type) and OT (Operational Transformation) algorithms for different data types: text, set, trees. The framework is able to evaluate the performance of comparable algorithms on different corpus of event traces. These event traces can be produced randomly according to different parameters, can be extracted from actual real-time editing session that have been recorded, or can be automatically extracted from distributed version control repositories such as the one produced with Git. Performances of the algorithms are measured in terms of execution time, memory footprint and quality of merge result (compared to manual merge history stored in git repositories).

- Participants: Pascal Urso and Gérald Oster
- Contact: Pascal Urso
- URL: https://github.com/score-team/replication-benchmarker/

4.5. Rivage

Real-tIme Vector grAphic Group Editor
FUNCTIONAL DESCRIPTION

Rivage is a real-time collaborative graphical editor. Several users can edit at the same time and in real-time a graphical document, user changes being immediately seen by the other users. The editor relies on a peer-to-peer architecture where users can join and leave the group at any time. Each user has a copy of the shared document and user changes on the document copies are merged in real-time by using a CRDT (Commutative Replicated Data Type) algorithm.

- Participant: Claudia-Lavinia Ignat
- Contact: Claudia-Lavinia Ignat
- URL: https://github.com/stephanemartin/rivage/

5. New Results

5.1. Evaluation and Design of Consistency Maintenance Algorithms for Complex Data

Participants: Luc André, Quang Vinh Dang, Claudia-Lavinia Ignat, Gérald Oster, Pascal Urso.

Since the Web 2.0 era, the Internet is a huge content editing place on which users collaborate. Such shared content can be edited by thousands of people. However, current consistency maintenance algorithms seem not to be adapted to massive collaborative updating involving large amounts of contributors and a high velocity of changes. This year we continued our work on the evaluation of existing collaborative editing approaches and on the design of new algorithms that overcome limitations of state of the art ones. We designed new optimistic replication algorithms for maintaining consistency for complex data such as wikis and strings and we evaluated existing algorithms in large scale settings.

Wikis are one of the most important tools of Web 2.0 allowing users to easily edit shared data. However, wikis offer limited support for merging concurrent contributions on the same pages. Users have to manually merge concurrent changes and there is no support for an automatic merging. Real-time collaborative editing reduces the number of conflicts as the time frame for concurrent work is very short. We proposed extending wiki systems with real-time collaboration and designed an automatic merging solution adapted for rich content wikis [5]. Our merging solution is based on an operational transformation approach for which we defined operations with high-level semantics capturing user intentions when editing wiki content such as move, merge and split. Our solution is the first one that deals with high level operations, existing approaches being limited to operations of insert, delete and update on textual documents.

Over the last years we designed a CRDT-based consistency maintenance algorithm for strings [20] for peer-to-peer large scale collaboration that is used by our MUTE collaborative editor which will be integrated in the virtual desktop of the OpenPaaS::NG project. This algorithm called LogootSplit can be seen as an extension for variable-sized elements (e.g. strings) of one of the first basic CRDT algorithms for unit elements (e.g. characters) proposed by our team called Logoot [32]. Its principles are general and can be applied to other basic CRDT algorithms. This year we proposed another algorithm for strings based on the RGA algorithm [9].

By means of simulations we measured the delays in popular real-time collaborative editing systems such as GoogleDocs and Etherpad [12] in terms of the number of users that edit a shared document and their typing frequency. Delays exist between the execution of one user's modification and the visibility of this modification to the other users. Such delays are in part fundamental to the network, as well as arising from the consistency maintenance algorithms and underlying architecture of collaborative editors. Results of this study support our team assertion that delay associated with conventional consistency maintenance algorithms will impede group performance.

5.2. Probabilistic Partial Orderings

Participants: Jordi Martori Adrian, Pascal Urso.

Ensuring reliable and ordered communication between computers usually requires acknowledgment messages. In systems with a high rate of broadcast communication, the cost of such acknowledgment messages can be large. We propose to use the causal ordering information required by some applications to detect and request missing messages. To circumscribe the number of unnecessary requests we combine local awareness and probabilistic methods. Our model allows us to obtain reliable communication within a latency equivalent to unordered communication and lower network usage than acknowledgment systems [18].

5.3. Computational Trust based on User Behavior

Participants: Quang Vinh Dang, Claudia-Lavinia Ignat.

We continued our investigation on computing a trust score for each user according to their behaviour during a collaborative task. Previously we proposed a contract-based collaboration model [31] where trust in users is established and adjusted based on their compliance to the contracts specified by the data owners when they share the data.

We continued this work by proposing an experimental design for testing the proposed trust-based collaboration model. We studied the trust game, a money exchange game that has been widely used in behavioural economics for studying trust and collaboration between humans. In this game, exchange of money is entirely attributable to the existence of trust between users. In the context of the trust game we proposed a trust metric that reflects user behaviours during the collaboration [10]. This metric is robust against fluctuating user behaviour. Our trust metric is the first one that was proposed in the context of the trust game in order to predict user behaviour.

In order to compute the trust score of users according to their contributions during a collaborative editing task, we need to evaluate the quality of the document content. As an initial work in this direction we investigated how to automatically assess the quality of Wikipedia articles in order to guide readers towards high quality articles and to suggest to authors which articles need to be improved. In this context we proposed two automatic assessment methods of the quality of Wikipedia articles. In the first approach we introduced readability features for a better prediction of quality [11]. The second approach is based on a deep-learning mechanism that automatically learns features from document contents rather than manually defining them [13], [4].

5.4. A model to secure collaborative resources within Enterprise Social Networks

Participants: Ahmed Bouchami, Olivier Perrin.

Enterprise social networks (ESN) are collaborative environments that raise major challenges to secure them. In his thesis [2], Ahmed Bouchami addressed the problem of authentication of digital identities within collaborative communities. He proposed an interoperable architecture for managing federated authentication, thus allowing each enterprise to preserve its (own) authentication mechanism and each principal to perform a single sign on authentication regarding different enterprises. He also proposed access control management. His flexible access control model is based on a set of identity attributes, and a formal language based on temporal logic. This model allows for checking the consistency of the policies defined. with the model.

Last, the access control system offers the ability to control the user-centric sharing policies through policies based on a risk management mechanism, which makes the access control mechanism dynamic. The risk mechanism is based on the NIST's risk definition with an alignment with a set of parameters that include access control in the ESN context. More precisely, the dynamic risk management includes, the collaborative resource's importance, the authentication system's vulnerabilities and trust level reflected through the behavior of each collaborative actor. On this latter aspect of trust, a reputation score is computed using the history of collaborative interactions of each subject of the collaborative environment. Finally, a prototype is available and was demonstrated within the OpenPaaS ESN project.

5.5. Risk management for the deployment of a business process in a multi-cloud context

Participants: Amina Ahmed Nacer, Claude Godart, Elio Goettelmann, Samir Youcef.

The lack of trust in cloud organizations is often seen as obstacle to SaaS developments. This work proposes an approach which supports a trust model and a business process model in order to allow the orchestration of trusted business process components in the cloud.

The contribution is threefold and consists in a method, a model and a framework. The method categorizes techniques to transform an existing business process into a risk-aware process model that takes into account security risks related to cloud environments. These techniques are partially described in the form of constraints to automatically support process transformation. The model formalizes the relations and the responsibilities between the different actors of the cloud. This allows to identify the different information required to assess and quantify security risks in cloud environments.

The framework is a comprehensive approach that decomposes a business process into fragments that can automatically be deployed on multiple clouds. The framework also integrates a selection algorithm that combines the security information of cloud offers and of the process with other quality of service criteria to generate an optimized configuration. It is implemented in a tool to assess cloud providers and decompose processes.

Rooted in past years work, we are contributing this year at the methodological and framework levels in two directions:

- At the methodological level, while our risk computing model rested previously only on data provided by cloud providers (provider-side risk model), we are developing a risk model integrating client-side knowledge (client-side risk model).
- At the framework level, we have integrated the ability to integrate fake BP fragments in the objective to increase the obfuscation of a deployed BP logic [15].

5.6. Cloud Provisioning for Elastic BPM

Participants: François Charoy, Samir Youcef, Guillaume Rosinosky.

Even though the cloud computing paradigm has proven benefits, it faces a serious problem that can compromise its commercial success. It concerns the lack of an efficient approach for using optimally the available resources. For this, several approaches have been proposed [29]. However, they suffer from several shortcomings. Often only one objective is taken into account, expressing all operations in terms of cost. Furthermore, business processes should be insured with elasticity and multi-tenancy mechanism while adjusting the available resources to the dynamic load distribution. We proposed to optimize two conflicting objectives, namely the number of migrations of tenants and the cost incurred using a set of resources. Our approach allows to take into account the multi-tenancy property and the Cloud computing elasticity, and is efficient as shown by an extensive experimentation based on real data from Bonita BPM customers [16]. In order to secure the scientific value of our findings we have set up a experimentation infrastructure for making repeatable experiments on the Cloud [17]

5.7. Orchestration of crowdsourcing activities

Participants: François Charoy, Kahina Bessai.

Crowdsourcing is an important paradigm in human problem solving using the Web. When they face a workload outburst, businesses may choose to outsource some or all of their process tasks to the crowd in order to maintain the quality of service promised for their customers. This may occur in situations like crisis management, when organizations are overloaded by a sudden event breakout. These tasks are generally difficult to implement as solution based on software service only. So, the use of crowdsourcing platform seems enticing. To ensure efficient and wise use of resources, methods assisting decision making need to be developed whose aim is to assist businesses in choosing the most knowledgeable workers. We addressed the resource allocation problem in crisis context by defining a delegation approach based on crowdsourcing as resource provider. We introduce a mathematical model for business process execution in crowd-sourcing context and an exact optimization algorithm. As the problem addressed is NP-complete, we proposed a more efficient algorithm that we validated through simulation [7]. Furthermore, to overcome the limitations of existing works we take into account the fact that business process tasks are ordered while optimizing the overall execution time of a given business process instance under budget constraint. We used a synthetic crowd model or valitation. We have also defined a model to validate our work for geo-crowdsourcing activities [8].

6. Bilateral Contracts and Grants with Industry

6.1. Bilateral Contracts with Industry

6.1.1. Industrial funding Groupe Open (2016–2019)

Groupe Open is a leading french company specialised in digital services and operations. The goal of the project is to propose an industrial composition model for APIs that takes into account the new constraints imposed by this new way to distribute and operate software. It will be based on a formal API contract along with trust and reputation attributes in order to allow consumers to anticipate risks regarding the quality and the safety of services. A PhD student is under recruitment for this project. Coast funding : 237,000 €

6.2. Bilateral Grants with Industry

6.2.1. CIFRE Grant with Bonitasoft

Participants: François Charoy, Samir Youcef, Guillaume Rosinosky.

Bonitasoft is a leading software company in the domain of open source Business Process Management Systems. The objective of this grant is to help Bonitasoft to support effective elastic BPM operation in the Cloud by leveraging the business knowledge, the process models and the execution history of process instances and correlate them with cloud resource consumption. Guillaume Rosinosky has been recruited as a PhD Student to work on this project. We will define models that will be validated based on a detailed analysis of existing use cases that we have started to collect from Bonitasoft and its clients.

7. Partnerships and Cooperations

7.1. Regional Initiatives

7.1.1. Region Lorraine TV Paint (2016–2017)

Participants: Claudia-Lavinia Ignat [contact], Gérald Oster, Quang Vinh Dang, Matthieu Nicolas.

Partners: TVPaint Development, Inria COAST project-team

Website: https://www.tvpaint.com/

This is a project in collaboration with TVPaint Development financed by Region Lorraine. The goal is to contribute to the creation of a collaborative system dedicated to animation movies, that allows to manipulate high quantities of digital artifacts in a collaborative way.

7.2. National Initiatives

7.2.1. OpenPaas NG (2015–2018)

Participants: Claudia-Lavinia Ignat, François Charoy [contact], Gérald Oster, Olivier Perrin, Jean-Philippe Eisenbarth, Phillippe Kalitine, Matthieu Nicolas, Mohammed Riyadh Abdmeziem, Kahina Bessai, Victorien Elvinger, Quentin Laporte Chabasse, Hoai Le Nguyen, Hoang Long Nguyen.

Partners: Linagora, XWiki SAS, Nexedi, COAST project-team (Université de Lorraine, LORIA), DaScim team (LIX).

Website: http://www.open-paas.org/

This project is financed by BpiFrance and involves French industrial leaders in open-source software development (Linagora, Nexedi, XWiki) and academic partners in collaborative work (COAST team) and recommender systems (DaScim team, LIX). The goal of the project is to develop next generation cloud enabled virtual desktop based on an Enterprise Social Network to provide advanced collaborative and recommendation services. COAST team is responsible of the work package dedicated to the design of the peer-to-peer collaborative middleware. In this context, we bring our expertise on data replication for collaborative data in peer-to-peer environments and on trust and access control and identity management in distributed collaborative information systems.

7.2.2. Inria ADT PLM (2014-2016)

Participants: Gérald Oster [contact], Matthieu Nicolas.

Partners: COAST project-team, MYRIADS project-team.

Website: https://github.com/BuggleInc/plm/

This work is performed jointly with Martin Quison (previously member of project-team VERIDIS, now Professor at ENS Rennes).

The Programmer's Learning Machine (PLM) is a software platform dedicated to computer programming education. This generic platform offers support to teachers for creating programming microworlds suitable to teaching courses. It features an integrated and graphical environment, providing a short feedback loop to students in order to improve the effectiveness of the autonomous learning process.

This project aims at establishing an experimental platform for studying the teaching of basic programming and a research instrument to design new collaborative learning environments.

7.3. European Initiatives

7.3.1. FP7 & H2020 Projects

7.3.1.1. SyncFree (2013-2016)

Participants: Pascal Urso [contact], Jordi Martori Adrian.

Program: FP7-ICT-2013-10

Project acronym: SyncFree

Project title: Large-scale computation without synchronisation

Duration : October 2013 - September 2016

Coordinator: Marc Shapiro, Inria

Other Partners: REGAL project-team (Inria Paris - Rocquencourt / LIP6, coordinator), Basho Technologies Limited (United Kingdom), Trifork AS (Denmark), Rovio Entertaiment OY (Finland), Faculdade de Ciências e Tecnologia (Universidade Nova de Lisboa, Portugal), Université Catholique de Louvain (Belgium), Ko c University (Turkey), Technische Universität Kaiserslautern (Germany) and COAST project-team.

Large-scale on-line services including social networks and multiplayer games handle huge quantities of frequently changing shared data. Maintaining their consistency is relatively simple in a centralised cloud, but no longer possible due to increased scalability requirements. Instead, data must be replicated across several distributed data centres, requiring new principled approaches to consistency that have been explored by the SyncFree project. http://syncfree.lip6.fr/

7.4. International Initiatives

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

7.4.1.1. USCOAST2

Title: User Studies on Trustworthy Collaborative Systems

International Partner (Institution - Laboratory - Researcher):

Wright State University (United States) - Department of Psychology, Knoesis - Valerie Shalin

Start year: 2016

See also: http://uscoast.loria.fr

The proposed project addresses the perception of trust by users, the appropriateness of a trust-based security approach and the role of trust metrics in the management of distributed work. The main challenge of this project is how to measure trust based on user behaviour and to verify by means of experimental studies with users that the trust-based mechanism is acceptable by users. We plan to apply this trust-based mechanism for two types of applications. The first one is collaborative editing where user trust will be computed based on the quality of user contributions for a document or project. The second type of application is in the management of work over a large group of people in order to conduct efficient, high-yield, high-density real time crowdsourcing activities.

Partners of USCOAST2 project have complementary expertise. Coast provides expertise in collaborative methods, systems and related technologies. Coast will propose algorithms that track and manipulate trust metrics. Kno.e.sis provides expertise on the analysis of human work-related behavior, including methods of data collection and data analysis, as well as a theoretical foundation for the evaluation of human performance. Knoesis will analyse trust from a psychological phenomenon point of view.

7.5. International Research Visitors

7.5.1. Visits to International Teams

7.5.1.1. Research Stays Abroad

- Claudia-Lavinia Ignat visited the Department of Computer Science & Knoesis, Wright State University for 1 month in the period June–July 2016 in the context of the associated team USCOAST2
- Gérald Oster visited the Department of Computer Science & Knoesis, Wright State University for 1 month in the period June–July 2016 in the context of the associated team USCOAST2

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Events Organisation

8.1.1.1. Member of the Organizing Committees

- François Charoy was co-chair of the PhD Forum for ICSOC 2016
- Claudia-Lavinia Ignat is in the organisation committee of The Fifteenth International Workshop on Collaborative Editing Systems in conjunction with CSCW 2017

8.1.2. Scientific Events Selection

8.1.2.1. Member of the conference program committees

- Claude Godart was PC member of the conference program committee of BPMDS (Business Process Modeling, Development and Support), EDOC (The enterprise computing conference), ICSOC (International Conference on Services Oriented Computing), IEEE CLOUD Computing, ICWS (IEEE International Conference on Web Services), SCC (IEEE International Conference on Services Computing), S2 ICIOT (S2 International Conference on Internet of Things), IEEE/WIC/ACM WI (Web Intelligence conference), WISE (Web Information Systems Engineering) conferences.
- Claudia-Lavinia Ignat was PC member of CSCW (International Conference on Computer Supported Cooperative Work and Social Computing) 2016, CDVE (International Conference on Cooperative Design, Visualization and Engineering) 2016, ICEBE (International Conference on e-Business Engineering) 2016 and The First IFIP Internet of People Workshop (IoP-W'16) in conjunction with Networking 2016 conference

- Olivier Perrin was PC Member of ICSOC 2016, I3E 2016 (15th IFIP Conference on e-Business, e-Services and e-Society), VECOS 2016 (10th International Workshop on Verification and Evaluation of Computer and Communication Systems), and some workshops.
- François Charoy was PC Member of ICEBE (International Conference on Business Engineering) 2016, CTS 2016 (International Symposium on Collaborative Technologies and Systems), DG.O (International Conference on Digital Government Research) 2016, IEEE WETICE 2016, ICSOC 2016, IEEE International Conference on Business Information Systems and of several workshops.
- Khalid Benali was PC Member of WorldCIST'16 (World Conference on Information Systems and Technologies), I-ESA'2016 (Interoperability of Enterprise Software and Applications), AFIN 2016 (International Conference on Advances in Future Internet), I3E 2016 (IFIP Conference on e-Business, e-Services and e-Society), ICICS 2016 (7th International Conference on Information and Communication Systems), MEDES 2016 (8th International Conference on Management of Digital EcoSystems), SYSCO'16 (third international conference on collaborative systems) and SoEA4EE'2016 (The 8th Workshop on Service oriented Enterprise Architecture for Enterprise Engineering).
- Gérald Oster was a PC member of CoopIS 2016 (International Conference on Cooperative Information Systems).

8.1.3. Journal

8.1.3.1. Member of the editorial boards

- Claude Godart is member of the editorial board of IEEE Transactions on Service Computing, International Journal of Services Computing, and member of the review board of the International Journal of Next Generation Computing.
- Claudia-Lavinia Ignat is member of the editorial board of Journal of CSCW (Computer Supported Cooperative Work).
- François Charoy is member of the editorial board of Service Oriented Computing and Applications Journal (Springer).

8.1.3.2. Reviewer - Reviewing activities

- In 2016, Olivier Perrin reviewed papers for IEEE Transactions on Services Computing journal, IEEE Transactions on Parallel and Distributed Systems and Journal of Systems and Software.
- In 2016, Claudia-Lavinia Ignat reviewed papers for Concurrency and Computation: Practice and Experience, World Wide Web Journal, CHI 2016 and CSCW 2017.
- In 2016, Gérald Oster reviewed papers for Computer Supported Cooperative Work Journal, Concurrency and Computation: Practice and Experience journal and CSCW 2017.

8.1.4. Invited talks

- François Charoy has been invited as a keynote Speaker at the IEEE WETICE Conference in Paris [6] on Collaborative Networks and Crisis Management.
- Claudia-Lavinia Ignat gave an invited lecture in May 2016 at SOAMED Graduate School in Berlin on Replicated Data Consistency
- Claudia-Lavinia Ignat gave an invited talk in June 2016 at the Department of Psychology, Wright State University, on Large-scale trust-based collaboration
- Claudia-Lavinia Ignat gave an invited talk in July 2016 at the Department of Computer Science and Engineering, Ohio Center of Excellence in Knowledge-enabled Computing (Kno.e.sis), Wright State University on Large-scale trust-based collaboration
- Gérald Oster gave an invited talk in July 2016 at the Department of Computer Science and Engineering, Ohio Center of Excellence in Knowledge-enabled Computing (Kno.e.sis), Wright State University on Distributed real-time collaborative editing

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

Permanent members of the COAST project-team are leading teachers in their respective institutions. They are responsible of lectures in disciplines like software engineering, database systems, object oriented programming and design, distributed systems, service computing and more advanced topics at all levels and in different of departments in the University. Most of the PhD Students have also teaching duties in the same institutions. As a whole, the COAST team accounts for more than 2500 hours of teaching. Members of the COAST team are also deeply involved in the pedagogical and administrative life of their departments.

- Gérôme Canals was the head of the Computer science department of the Nancy-Charlemagne University Institute of Technology (IUT Nancy Charlemagne) since September 2010 and until August 2016, and is responsible for the professional licence degree “Web application programming” since sept. 2001.
- Claude Godart is responsible for the Computer Science department of the engineering school ESSTIN.
- Khalid Benali is responsible for the professional Master degree speciality “Distributed Information Systems” of MIAGE and of its international branch in Morocco.
- François Charoy is responsible of the Software Engineering specialisation at the TELECOM Nancy Engineering School of University of Lorraine.
- Pascal Urso is responsible for the “Security, Services, Systems and Network” track of the master degree in computer science at University of Lorraine since September 2013.

8.2.2. Supervision

PhD (in progress): Quang Vinh Dang, Trust-based large scale collaboration, started in 10/2014, Claudia-lavinia Ignat and François Charoy

PhD (in progress): Hoai Le Nguyen, Study of group performance and behavior in collaborative editing, started in 9/2015, Claudia-Lavinia Ignat and François Charoy

PhD (in progress): Hoang Long Nguyen, A Trust Based Authorization Model and Framework for the Cloud, started in 11/2015, Claudia-Lavinia Ignat and Olivier Perrin

PhD (defended): Luc André, Replication and Consistency Maintenance in Peer-to-Peer Collaborative Environment, started in 9/2011, François Charoy and Gérald Oster

PhD (in progress): Victorien Elvinger, Secured Replication for Peer-to-Peer Collaborative Infrastructures, started in 10/2015, François Charoy and Gérald Oster

PhD (defended): Ahmed Bouchami , Sécurité des données collaboratives d’une plateforme PaaS, started in 11/2012, Olivier Perrin

PhD (in progress): Jordi Martori i Adrian, Data constraints for large-scale collaboration, started in 10/2013, François Charoy and Pascal Urso

PhD (in progress): Guillaume Rosinoski, Elastic BPM and the Cloud, started in 10/2014, François Charoy and Samir Youssef

PhD (in progress): Quentin Laporte-Chabasse, Federation of Organisations over Peer to Peer Collaborative Network, started in 10/2016, François Charoy and Gérald Oster

PhD (in progress): Béatrice Linot, Trust in cooperative systems, Jérome Dinet et François Charoy, started 11/2016

8.2.3. Juries

- François Charoy was head of the Selection committee at TELECOM Nancy, Université de Lorraine

COAST members were members of the following PhD and HdR defense committees:

- Mondi Ravi, PhD, Université de Grenoble, January 2016 (François Charoy)

- Tomasz Buchert, PhD, Université de Lorraine, January 2016 (François Charoy)
- Luc André, PhD, Université de Lorraine, May 2016 (François Charoy and Gérald Oster)
- Adrian Shatte, PhD, James Cook University, Cairns, Australia, September 2016 (François Charoy)
- Wassim Derguech, PhD, National University of Ireland, Galway, Ireland, December 2016 (François Charoy)
- Philippe Dirix, PhD, Université de Lille, July 2016 (Khalid Benali)
- Bouchra El Idrissi, PhD, Université Mohammed V de Rabat, Maroc, September 2016 (Khalid Benali)
- Ghada Gharbi, PhD, Université de Toulouse 3, November 2016 (Claude Godart)
- Hind Benfenatki, PhD, Université de Lyon 1, December 2016 (Claude Godart)
- Brice Nedelec, PhD, Université de Nantes, October 2016 (Gérald Oster)
- Anthéa Mayzaud, PhD, Université de Lorraine, October 2016 (Olivier Perrin)
- Noran Azmy, PhD, Universität des Saarlandes and Université de Lorraine, November 2016 (Olivier Perrin)

8.3. Popularization

- In March 2016 members of the team (François Charoy and Phillippe Kalitine) participated to the "Rencontres Université Entreprise" in Paris to demonstrate the collaborative editor MUTE (http://www.rue-aef.com)
- In January 2016 Claudia-Lavinia Ignat presented Coast research activities to the first year students at Ecole de Mines de Nancy
- In May 2016 Claudia-Lavinia Ignat gave a lecture on Replicated Data Consistency at SOAMED Graduate School in Berlin
- In May 2016 Claudia-Lavinia Ignat organised the meeting Research@Inria at Inria Nancy-Grand Est for presenting to internship students, PhD students and postdocs various Inria programs and the main research topics at Inria with a focus on activities of research teams at Inria Nancy-Grand Est. She also presented the main activities of a researcher and briefly described her research work.
- In November 2016 members of the team (François Charoy and Matthieu Nicolas) participated to the "Rencontre Inria-Industrie" (RII) on the topic - Interactions avec les objets et services numériques" in Lille to demonstrate MUTE collaborative editor
- In December 2016 members of the team (Claudia-Lavinia Ignat, Gérald Oster, Matthieu Nicolas and Phillippe Kalitine) participated to the "Rencontre Inria-Industrie" (RII) on the topic - Nouvelles technologies pour la protection des données et des systèmes numériques" in Nancy to demonstrate collaborative editor MUTE
- In December 2016 members of the team (Gérald Oster, Matthieu Nicolas and Phillippe Kalitine) demonstrated the collaborative editor MUTE during the visit of the Rectors of the Mexican Technological Universities at LORIA in the context of the bilateral MEXPROTEC program.

8.4. Institutional commitment

- Claudia-Lavinia Ignat is in charge of European affairs for Inria Nancy Grand-Est. She is the Delegate of International Relations for Inria Nancy-Grand Est and member of COST-GTRI commission. She is member of the Inria Nancy-Grand Est COMIPERS committee. She participated to a working group in charge with the design of a booklet for industrials describing the technological offer of Inria Nancy-Grand Est (she was responsible for the part concerning Large-scale collaborative services and systems). She is responsible with the activity kindergarten at AGOS Inria Nancy-Grand Est.

9. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] L. ANDRÉ.*Intention Preservation and Consistency Maintenance for Real-Time Replicated Data*, Université de Lorraine (Nancy), May 2016, https://tel.archives-ouvertes.fr/tel-01362437.

[2] A. BOUCHAMI.*Security of collaborative resources in enterprises social networks*, Université de lorraine, September 2016, https://tel.archives-ouvertes.fr/tel-01402629.

Articles in International Peer-Reviewed Journal

[3] N. BOUDJLIDA, B. GASMI BOUMEZOUED.*Conceptual Graphs for Fomally Managing and Discovering Complementary Competences*, in "Springer LNAI", 2016, https://hal.inria.fr/hal-01253436.

[4] Q.-V. DANG, C.-L. IGNAT.*Quality Assessment of Wikipedia Articles: A Deep Learning Approach*, in "ACM SIGWEB Newsletter (ACM Digital Library)", November 2016 [*DOI :* 10.1145/2996442.2996447], https://hal.archives-ouvertes.fr/hal-01393227.

[5] C.-L. IGNAT, L. ANDRÉ, G. OSTER.*Enhancing rich content wikis with real-time collaboration*, in "Concurrency and Computation: Practice and Experience", 2016, https://hal.inria.fr/hal-01404024.

Invited Conferences

[6] F. CHAROY.*Keynote : From group collaboration to large scale social collaboration*, in "25th IEEE International Conference on Enabling Technologies: Infrastructure for Collaborative Enterprises (WETICE-2016)", Paris, France, June 2016, https://hal.inria.fr/hal-01342751.

International Conferences with Proceedings

[7] K. BESSAI, F. CHAROY.*Business process tasks-assignment and resourceallocation in Crowdsourcing context*, in "IEEE International Conference on Collaboration and Internet Computing", Pittsburgh, United States, November 2016, https://hal.archives-ouvertes.fr/hal-01401246.

[8] K. BESSAI, F. CHAROY.*Optimization of Orchestration of Geocrowdsourcing Activities*, in "Third International Conference on Information Systems for Crisis Response and Management in Mediterranean Countries (ISCRAM-med 2016)", Madrid, Spain, Lecture Notes in Business Information Processing, Springer, October 2016, https://hal.inria.fr/hal-01356053.

[9] L. BRIOT, P. URSO, M. SHAPIRO.*High Responsiveness for Group Editing CRDTs*, in "ACM International Conference on Supporting Group Work", Sanibel Island, FL, United States, November 2016 [*DOI :* 10.1145/2957276.2957300], https://hal.inria.fr/hal-01343941.

[10] Q.-V. DANG, C.-L. IGNAT.*Computational Trust Model for Repeated Trust Games*, in "The 15th IEEE International Conference on Trust, Security and Privacy in Computing and Communications (TrustCom-16)", Tianjin, China, Proceedings of the 15th IEEE International Conference on Trust, Security and Privacy in Computing and Communications, August 2016, https://hal.inria.fr/hal-01351250.

[11] Q.-V. DANG, C.-L. IGNAT.*Measuring Quality of Collaboratively Edited Documents: the case of Wikipedia*, in "Proceedings of the 2nd IEEE International Conference on Collaboration and Internet Computing (CIC-16)", Pittsburgh, United States, November 2016, https://hal.archives-ouvertes.fr/hal-01388614.

[12] Q.-V. DANG, C.-L. IGNAT.*Performance of real-time collaborative editors at large scale: User perspective*, in "Internet of People Workshop, 2016 IFIP Networking Conference", Vienna, Austria, Proceedings of 2016 IFIP Networking Conference, Networking 2016 and Workshops, May 2016, p. 548-553 [*DOI :* 10.1109/IFIPNETWORKING.2016.7497258], https://hal.inria.fr/hal-01351229.

[13] Q.-V. DANG, C.-L. IGNAT.*Quality Assessment of Wikipedia Articles without Feature Engineering*, in "Proceedings of the 16th ACM/IEEE-CS on Joint Conference on Digital Libraries", Newark, United States, ACM, June 2016, p. 27-30 [*DOI :* 10.1145/2910896.2910917], https://hal.inria.fr/hal-01351226.

[14] M. GAUTIER, B. WROBEL-DAUTCOURT.*artEoz - dynamic program visualization*, in "International Conference on Informatics in Schools: Situation, Evolution, and Perspectives, ISSEP 2016", Munster, Germany, October 2016, 2, https://hal.inria.fr/hal-01388703.

[15] A. A. NACER, E. GOETTELMANN, S. YOUCEF, A. TARI, C. GODART.*Obfuscating a Business Process by Splitting Its Logic with Fake Fragments for Securing a Multi-cloud Deployment*, in "IEEE Congress On Services", SanFrancisco, United States, Services (SERVICES), 2016 IEEE World Congress on, June 2016, p. 18 - 25 [*DOI :* 10.1109/SERVICES.2016.9], https://hal.univ-lorraine.fr/hal-01399380.

[16] G. ROSINOSKY, S. YOUCEF, F. CHAROY.*An Efficient Approach for Multi-tenant Elastic Business Processes Management in Cloud Computing environment*, in "9th IEEE International Conference on Cloud Computing - IEEE Cloud 2016", San Francisco, United States, June 2016, https://hal.inria.fr/hal-01355125.

Conferences without Proceedings

[17] G. ROSINOSKY, S. YOUCEF, F. CHAROY.*A Framework for BPMS Performance and Cost Evaluation on the Cloud*, in "Workshop "Business Process Monitoring and Performance Analysis in the Cloud"", Luxembourg, Luxembourg, IEEE CloudCom, December 2016, https://hal.archives-ouvertes.fr/hal-01379167.

Research Reports

[18] J. MARTORI, P. URSO.*Reliable causal delivery with probabilistic design*, Inria Nancy, November 2016, n° RR-8985, https://hal.inria.fr/hal-01405896.

Other Publications

[19] G. ROSINOSKY, S. YOUCEF, F. CHAROY.*An Efficient Approach for Multi-tenant Elastic Business Processes Management in Cloud Computing environment*, February 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01300188.

References in notes

[20] L. ANDRÉ, S. MARTIN, G. OSTER, C.-L. IGNAT.*Supporting Adaptable Granularity of Changes for Massive-scale Collaborative Editing*, in "CollaborateCom - 9th IEEE International Conference on Collaborative Computing: Networking, Applications and Worksharing - 2013", Austin, United States, October 2013, http://hal.inria.fr/hal-00903813.

[21] S. BHIRI, W. GAALOUL, C. GODART. *Mining and Improving Composite Web Services Recovery Mechanisms*, in "International Journal of Web Services Research", 03 2008, vol. 3, http://hal.inria.fr/inria-00438424/en/.

[22] S. BHIRI, O. PERRIN, W. GAALOUL, C. GODART. *An Object-Oriented Metamodel For Inter-Enterprises Cooperative Processes Based on Web Services*, in "Journal of Integrated Design and Process Science", 2004, vol. 8, p. 37–55, http://hal.inria.fr/inria-00099953/en/.

[23] F. CASATI. *Promises and Failures of Research in Dynamic Service Composition*, in "Seminal Contributions to Information Systems Engineering", J. BUBENKO, J. KROGSTIE, O. PASTOR, B. PERNICI, C. ROLLAND, A. SØLVBERG (editors), Springer Berlin Heidelberg, 2013, p. 235-239, http://dx.doi.org/10.1007/978-3-642-36926-1_18.

[24] C. A. ELLIS, S. J. GIBBS. *Concurrency Control in Groupware Systems*, in "Proceedings of the ACM SIGMOD Conference on the Management of Data - SIGMOD 89", Portland, Oregon, USA, May 1989, p. 399–407, http://doi.acm.org/10.1145/67544.66963.

[25] G. OSTER, P. URSO, P. MOLLI, A. IMINE. *Data Consistency for P2P Collaborative Editing*, in "ACM Conference on Computer-Supported Cooperative Work - CSCW 2006", Banff, Alberta, Canada, ACM Press, 11 2006, p. 259 - 268, http://hal.inria.fr/inria-00108523/en/.

[26] M. P. PAPAZOGLOU, P. TRAVERSO, S. DUSTDAR, F. LEYMANN. *Service-Oriented Computing: State of the Art and Research Challenges*, in "Computer", 2007, vol. 40, p. 38-45.

[27] N. PREGUIÇA, J. M. MARQUÈS, M. SHAPIRO, M. LETIA. *A commutative replicated data type for cooperative editing*, in "29th IEEE International Conference on Distributed Computing Systems (ICDCS 2009)", Montreal, Québec Canada, IEEE Computer Society, 2009, p. 395-403 [*DOI :* 10.1109/ICDCS.2009.20], http://hal.inria.fr/inria-00445975/en/.

[28] Y. SAITO, M. SHAPIRO. *Optimistic Replication*, in "Computing Surveys", March 2005, vol. 37, n° 1, p. 42–81, http://doi.acm.org/10.1145/1057977.1057980.

[29] S. SCHULTE, C. JANIESCH, S. VENUGOPAL, I. WEBER, P. HOENISCH. *Elastic Business Process Management: State of the art and open challenges for BPM in the cloud*, in "Future Generation Computer Systems", 2015, vol. 46, p. 36 - 50 [*DOI :* 10.1016/J.FUTURE.2014.09.005], http://www.sciencedirect.com/science/article/pii/S0167739X1400168X.

[30] C. SUN, X. JIA, Y. ZHANG, Y. YANG, D. CHEN. *Achieving Convergence, Causality Preservation, and Intention Preservation in Real-Time Cooperative Editing Systems*, in "ACM Transactions on Computer-Human Interaction", March 1998, vol. 5, n° 1, p. 63–108, http://doi.acm.org/10.1145/274444.274447.

[31] H. T. T. TRUONG. *A Contract-based and Trust-aware Collaboration Model*, Université de Lorraine, December 2012, https://tel.archives-ouvertes.fr/tel-00769076.

[32] S. WEISS, P. URSO, P. MOLLI. *Logoot: A Scalable Optimistic Replication Algorithm for Collaborative Editing on P2P Networks*, in "29th IEEE International Conference on Distributed Computing Systems - ICDCS 2009", Montreal, Canada, IEEE, June 2009, p. 404-412 [*DOI :* 10.1109/ICDCS.2009.75], https://hal.inria.fr/inria-00432368.

Team LARSEN

Lifelong Autonomy and interaction skills for Robots in a Sensing ENvironment

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
Nancy - Grand Est

THEME
Robotics and Smart environments

Table of contents

Team LARSEN

Creation of the Team: 2015 January 01

Keywords:

Computer Science and Digital Science:

3.4.1. - Supervised learning
3.4.3. - Reinforcement learning
3.4.4. - Optimization and learning
3.4.5. - Bayesian methods
3.4.6. - Neural networks
5.10. - Robotics
5.10.2. - Perception
5.10.3. - Planning
5.10.4. - Robot control
5.10.5. - Robot interaction (with the environment, humans, other robots)
5.10.6. - Swarm robotics
5.10.7. - Learning
5.10.8. - Cognitive robotics and systems
5.11. - Smart spaces
5.11.1. - Human activity analysis and recognition
8.2. - Machine learning
8.5. - Robotics
8.7. - AI algorithmics

Other Research Topics and Application Domains:

2.1. - Well being
2.5. - Handicap and personal assistances
2.5.3. - Assistance for elderly
2.8. - Sports, performance, motor skills
5.1. - Factory of the future
5.6. - Robotic systems

1. Members

Research Scientists

François Charpillet [Team leader, Inria, Senior Researcher, HDR]
Francis Colas [Inria, Researcher]
Serena Ivaldi [Inria, Researcher]
Jean-Baptiste Mouret [Inria, Researcher, HDR]

Faculty Members

Amine Boumaza [Univ. Lorraine, Associate Professor]
Karim Bouyarmane [Univ. Lorraine, Associate Professor, from Sep 2016]
Vincent Thomas [Univ. Lorraine, Associate Professor]

Technical Staff

Dorian Goepp [Inria]
Mélanie Lelaure [Inria, until Sep 2016]
Thomas Moinel [Inria]

PhD Students

Adrian Bourgaud [Inria]
Konstantinos Chatzilygeroudis [Inria]
Oriane Dermy [Inria]
Abdallah Dib [Inria, until May 2016]
Yassine El Khadiri [Inria, from Nov 2016]
Iñaki Fernández Pérez [Univ. Lorraine]
Nassim Kaldé [Univ. Lorraine]
Rituraj Kaushik [Inria, from Oct 2016]
Van Quan Nguyen [Inria]

Post-Doctoral Fellows

Xuan Son Nguyen [Univ. Lorraine, ATER, until Sep 2016]
Vassilis Vassiliades [Inria]

Visiting Scientists

Ioannis Hatzilygeroudis [University of Patras, Sep 2016]
Valerio Modugno [Sapienza, PhD student]
Francesco Nori [Italian Institute of Technology, until Feb 2016]
John Rieffel [Union College, from May 2016 until Jun 2016]
Jamie Waugh [University of Waterloo, Visiting PhD student, from Sep 2016]

Administrative Assistants

Véronique Constant [Inria]
Christelle Lévêque [Univ. Lorraine]

Others

Federico Allocati [Inria, internship, until Mar 2016]
Ugo Chervet [Inria, internship, from Mar 2016 until Sep 2016]
Virgile Dauge [Inria, internship, from Apr 2016 until Sep 2016]
Alexis Grall [Inria, internship, from May 2016 until Sep 2016]
Mohammad Rami Koujan [Inria, internship, from Jun 2016 until Sep 2016]
Jules Kozolinsky [ENS Cachan, internship, from Jun 2016 until Jul 2016]
Adrien Malaise [Inria, internship, from Feb 2016 until Aug 2016]
Sebastian Marichal [Inria, internship]
Vaios Papaspyros [Inria, internship, from May 2016 until Oct 2016]
Roberto Rama [Inria, internship, from Jun 2016]
Anthony Voilque [Inria, internship, from Mar 2016 until Sep 2016]

2. Overall Objectives

2.1. Overall Objectives

The goal of the LARSEN team is to move robots beyond the research laboratories and manufacturing industries: current robots are far from being the fully autonomous, reliable, and interactive robots that could co-exist with us in our society and run for days, weeks, or months. While there is undoubtedly progress to be made on the hardware side, robotics platforms are quickly maturing and we believe the main challenges to achieve our goal are now on the software side. We want our software to be able to run on low-cost mobile robots that are therefore not equipped with high-performance sensors or actuators, so that our techniques can realistically be deployed and evaluated in real settings, such as in service and assistive robotic applications. We envision that these robots will be able to cooperate with each other but also with intelligent spaces or apartments which can also be seen as robots spread in the environments. Like robots, intelligent spaces are equipped with sensors that make them sensitive to human needs, habits, gestures, etc., and actuators to be adaptive and responsive to environment changes and human needs. These intelligent spaces can give robots improved skills, with less expensive sensors and actuators enlarging their field of view of human activities, making them able to behave more intelligently and with better awareness of people evolving in their environment. As robots and intelligent spaces share common characteristics, we will use, for the sake of simplicity, the term robot for both mobile robots and intelligent spaces.

Among the particular issues we want to address, we aim at designing robots having the ability to:

- handle dynamic environment and unforeseen situations;
- cope with physical damage;
- interact physically and socially with humans;
- collaborate with each other;
- exploit the multitude of sensors measurements from their surrounding;
- enhance their acceptability and usability by end-users without robotics background.

All these abilities can be summarized by the following two objectives:

- *life-long autonomy*: continuously perform tasks while adapting to sudden or gradual changes in both the environment and the morphology of the robot;
- *natural interaction with robotics systems*: interact with both other robots and humans for long periods of time, taking into account that people and robots learn from each other when they live together.

3. Research Program

3.1. Lifelong Autonomy

3.1.1. Scientific Context

So far, only a few autonomous robots have been deployed for a long time (weeks, months, or years) outside of factories and laboratories. They are mostly mobile robots that simply “move around” (e.g., vacuum cleaners or museum “guides”) and data collecting robots (e.g., boats or underwater “gliders” that collect data about the water of the ocean).

A large part of the long-term autonomy community is focused on simultaneous localization and mapping (SLAM), with a recent emphasis on changing and outdoor environments [39], [50]. A more recent theme is life-long learning: during long-term deployment, we cannot hope to equip robots with everything they need to know, therefore some things will have to be learned along the way. Most of the work on this topic leverages machine learning and/or evolutionary algorithms to improve the ability of robots to react to unforeseen changes [39], [48].

3.1.2. Main Challenges

The first major challenge is to endow robots with a stable situation awareness in open and dynamic environments. This covers both the state estimation of the robot itself as well as the perception/representation of the environment. Both problems have been claimed to be solved but it is only the case for static environments [47].

In the LARSEN team, we aim at deployment in environments shared with humans which imply dynamic objects that degrade both the mapping and localization of a robot, especially in cluttered spaces. Moreover, when robots stay longer in the environment than for the acquisition of a snapshot map, they have to face structural changes, such as the displacement of a piece of furniture or the opening or closing of a door. The current approach is to simply update an implicitly static map with all observations with no attempt at distinguishing the suitable changes. For localization in not-too-cluttered or not-too-empty environments, this is generally sufficient as a significant fraction of the environment should remain stable. But for life-long autonomy, and in particular navigation, the quality of the map, and especially the knowledge of the stable parts, is primordial.

A second major obstacle to move robots outside of labs and factories is their fragility: current robots often break in a few hours, if not a few minutes. This fragility mainly stems from the overall complexity of robotic systems, which involve many actuators, many sensors, and complex decisions, and from the diversity of situations that robots can encounter. Low-cost robots exacerbate this issue because they can be broken in many ways (high-quality material is expensive), because they have low self-sensing abilities (sensors are expensive and increase the overall complexity), and because they are typically targeted towards non-controlled environments (e.g., houses rather than factories, in which robots are protected from most unexpected events). More generally, this fragility is a symptom of the lack of adaptive abilities in current robots.

3.1.3. Angle of Attack

To solve the state estimation problem, our approach is to combine classical estimation filters (Extended Kalman Filters, Unscented Kalman Filters, or particle filters) with a Bayesian reasoning model in order to internally simulate various configurations of the robot in its environment. This should allow for adaptive estimation that can be used as one aspect of long-term adaptation. To handle dynamic and structural changes in an environment, we aim at assessing, for each piece of observation, whether it is static or not.

We also plan to address active sensing to improve the situation awareness of robots. Literally, active sensing is the ability of an interacting agent to act so as to control what it senses from its environment with the typical objective of acquiring information about this environment. A formalism for representing and solving active sensing problems has already been proposed by members of the team [38] and we aim to use this to formalize decision making problems of improving situation awareness.

Situation awareness of robots can also be tackled by cooperation, whether it be between robots or between robots and sensors in the environment (led out intelligent spaces) or between robots and humans. This is in rupture with classical robotics, in which robots are conceived as self-contained. But, in order to cope with as diverse environments as possible, these classical robots use precise, expensive, and specialized sensors, whose cost prohibits their use in large-scale deployments for service or assistance applications. Furthermore, when all sensors are on the robot, they share the same point of view on the environment, which is a limit for perception. Therefore, we propose to complement a cheaper robot with sensors distributed in a target environment. This is an emerging research direction that shares some of the problematics of multi-robot operation and we are therefore collaborating with other teams at Inria that address the issue of communication and interoperability.

To address the fragility problem, the traditional approach is to first diagnose the situation, then use a planning algorithm to create/select a contingency plan. But, again, this calls for both expensive sensors on the robot for the diagnosis and extensive work to predict and plan for all the possible faults that, in an open and dynamic environment, are almost infinite. An alternative approach is then to skip the diagnosis and let the robot discover by trial and error a behavior that works in spite of the damage with a reinforcement learning algorithm [57], [48]. However, current reinforcement learning algorithms require hundreds of trials/episodes to learn a single, often simplified, task [48], which makes them impossible to use for real robots and more ambitious tasks. **We therefore need to design new trial-and-error algorithms that will allow robots to learn with a much smaller number of trials (typically, a dozen).** We think the key idea is to guide online learning on the physical robot with dynamic simulations. For instance, in our recent work, we successfully mixed evolutionary search in simulation, physical tests on the robot, and machine learning to allow a robot to recover from physical damage [49], [2].

A final approach to address fragility is to deploy several robots or a swarm of robots or to make robots evolve in an active environment. We will consider several paradigms such as (1) those inspired from collective natural phenomena in which the environment plays an active role for coordinating the activity of a huge number of biological entities such as ants and (2) those based on online learning [46]. We envision to transfer our knowledge of such phenomenon to engineer new artificial devices such as an intelligent floor (which is in fact a spatially distributed network in which each node can sense, compute and communicate with contiguous nodes and can interact with moving entities on top of it) in order to assist people and robots (see the principle in [55], [46], [37]).

3.2. Natural Interaction with Robotic Systems

3.2.1. Scientific Context

Interaction with the environment is a primordial requirement for an autonomous robot. When the environment is sensorized, the interaction can include localizing, tracking, and recognizing the behavior of robots and humans. One specific issue lies in the lack of predictive models for human behavior and a critical constraint arises from the incomplete knowledge of the environment and the other agents.

On the other hand, when working in the proximity of or directly with humans, robots must be capable of safely interacting with them, which calls upon a mixture of physical and social skills. Currently, robot operators are usually trained and specialized but potential end-users of robots for service or personal assistance are not skilled robotics experts, which means that the robot needs to be accepted as reliable, trustworthy and efficient [61]. Most Human-Robot Interaction (HRI) studies focus on verbal communication [56] but applications such as assistance robotics require a deeper knowledge of the intertwined exchange of social and physical signals to provide suitable robot controllers.

3.2.2. Main Challenges

We are here interested in building the bricks for a situated Human-Robot Interaction (HRI) addressing both the physical and social dimension of the close interaction, and the cognitive aspects related to the analysis and interpretation of human movement and activity.

The combination of physical and social signals into robot control is a crucial investigation for assistance robots [58] and robotic co-workers [53]. A major obstacle is the control of physical interaction (precisely, the control of contact forces) between the robot and the human while both partners are moving. In mobile robots, this problem is usually addressed by planning the robot movement taking into account the human as an obstacle or as a target, then delegating the execution of this “high-level” motion to whole-body controllers, where a mixture of weighted tasks is used to account for the robot balance, constraints, and desired end-effector trajectories [43].

The first challenge is to make these controllers easier to deploy in real robotics systems, as currently they require a lot of tuning and can become very complex to handle the interaction with unknown dynamical systems such as humans. Here, the key is to combine machine learning techniques with such controllers.

The second challenge is to make the robot react and adapt online to the human feedback, exploiting the whole set of measurable verbal and non-verbal signals that humans naturally produce during a physical or social interaction. Technically, this means finding the optimal policy that adapts the robot controllers online, taking into account feedback from the human. Here, we need to carefully identify the significant feedback signals or some metrics of human feedback. In real-world conditions (i.e., outside the research laboratory environment) the set of signals is technologically limited by the robot’s and environmental sensors and the onboard processing capabilities.

The third challenge is for a robot to be able to identify and track people on board. The motivation is to be able to estimate online either the position, the posture, or even moods and intentions of persons surrounding the robot. The main challenge is to be able to do that online, in real-time and in cluttered environments.

3.2.3. Angle of Attack

Our key idea is to exploit the physical and social signals produced by the human during the interaction with the robot and the environment in controlled conditions, to learn simple models of human behavior and consequently to use these models to optimize the robot movements and actions. In a first phase, we will exploit human physical signals (e.g., posture and force measurements) to identify the elementary posture tasks during balance and physical interaction. The identified model will be used to optimize the robot whole-body control as prior knowledge to improve both the robot balance and the control of the interaction forces. Technically, we will combine weighted and prioritized controllers with stochastic optimization techniques. To adapt online the control of physical interaction and make it possible with human partners that are not robotics experts, we will exploit verbal and non-verbal signals (e.g., gaze, touch, prosody). The idea here is to estimate online from these signals the human intent along with some inter-individual factors that the robot can exploit to adapt its behavior, maximizing the engagement and acceptability during the interaction.

Another promising approach already investigated in the LARSEN team is the capability for a robot and/or an intelligent space to localize humans in its surrounding environment and to understand their activities. This is an important issue to handle both for safe and efficient human-robot interaction.

Simultaneous Tracking and Activity Recognition (STAR) [60] is an approch we want to develop. The activity of a person is highly correlated with his position, and this approach aims at combining tracking and activity recognition to benefit one from another. By tracking the individual, the system may help infer its possible activity, while by estimating the activity of the individual, the system may make a better prediction of his possible future positions (which can be very effective in case of occlusion). This direction has been tested with simulator and particle filters [45], and one promising direction would be to couple STAR with decision making formalisms like partially observable Markov decision processes, POMDPs). This would allow to formalize problems such as deciding which action to take given an estimate of the human location and activity. This could also formalize other problems linked to the active sensing direction of the team: how the robotic system might choose its actions in order to have a better estimate of the human location and activity (for instance by moving in the environment or by changing the orientation of its cameras)?

Another issue we want to address is robotic human body pose estimation. Human body pose estimation consists of tracking body parts by analyzing a sequence of input images from single or multiple cameras.

Human posture analysis is of high value for human robot interaction and activity recognition. However, even if the arrival of new sensors like RGB-D cameras has simplified the problem, it still poses a great challenge, especially if we want to do it online, on a robot and in realistic world conditions (cluttered environment). This is even more difficult for a robot to bring together different capabilities both at the perception and navigation level [44]. This will be tackled through different techniques, going from Bayesian state estimation (particle filtering), to learning, active and distributed sensing.

4. Application Domains

4.1. Personal Assistance

During the last fifty years, many medical advances as well as the improvement of the quality of life have resulted in a longer life expectancy in industrial societies. The increase in the number of elderly people is a matter of public health because although elderly people can age in good health, old age also causes embrittlement, in particular on the physical plan which can result in a loss of autonomy. That will force us to re-think the current model regarding the care of elderly people. [0] Capacity limits in specialized institutes, along with the preference of elderly people to stay at home as long as possible, explain a growing need for specific services at home.

Ambient intelligence technologies and robotics could contribute to this societal challenge. The spectrum of possible actions in the field of elderly assistance is very large. We will focus on activity monitoring services, mobility or daily activity aids, medical rehabilitation, and social interactions. This will be based on the experimental infrastructure we have build in Nancy (Smart apartment platform) as well as the deep collaboration we have with OHS. [0]

4.2. Civil Robotics

Many applications for robotics technology exist within the services provided by national and local government. Typical applications include civil infrastructure services [0] such as: urban maintenance and cleaning; civil security services; emergency services involved in disaster management including search and rescue; environmental

[0]See the Robotics 2020 Multi-Annual Roadmap [51], section 2.7.
[0]OHS (*Office d'Hygiène Sociale*) is an association managing several rehabilitation or retirement home structures.
[0]See the Robotics 2020 Multi-Annual Roadmap [51], section 2.5.

services such as surveillance of rivers, air quality, and pollution. These applications may be carried out by a wide variety of robot and operating modality, ranging from single robots or small fleets of homogeneous or heterogeneous robots. Often robot teams will need to cooperate to span a large workspace, for example in urban rubbish collection, and operate in potentially hostile environments, for example in disaster management. These systems are also likely to have extensive interaction with people and their environments.

The skills required for civil robots match those developed in the LARSEN project: operating for a long time in potentially hostile environment, potentially with small fleets of robots, and potentially in interaction with people.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Awards

- "Prix La Recherche 2016" (mention "sciences de l'information"), to Jean-Baptiste Mouret and his co-authors (Antoine Cully, Jeff Clune, Danesh Tarapore) for the article "Robots that can adapt like animals" (Nature, 2015).
- "2016 ISAL Award for Outstanding Paper of 2015 in the field of Artificial Life", awarded by the International Society for Artificial Life to Jean-Baptiste Mouret and his co-authors (Antoine Cully, Jeff Clune, Danesh Tarapore) for the article "Robots that can adapt like animals" (Nature, 2015).

6. New Software and Platforms

6.1. Limbo

LIbrary for Model-based Bayesian Optimization
KEYWORDS: Black-box optimization - C++ - Global optimization - Machine learning - Policy Learning - Bayesian optimization
FUNCTIONAL DESCRIPTION

Limbo is an open-source C++11 library for Bayesian optimization which is designed to be both highly flexible and very fast. It can be used to optimize functions for which the gradient is unknown, evaluations are expensive, and where runtime cost matters (e.g., on embedded systems or robots). Benchmarks on standard functions show that Limbo is about 2 times faster than BayesOpt (another C++ library) for a similar accuracy.

- Partners: Imperial College London - UPMC
- Contact: Jean-Baptiste Mouret
- URL: http://www.resibots.eu/limbo

6.2. sferes2

A lightweight generic C++ framework for evolutionary computation
FUNCTIONAL DESCRIPTION

Sferes2 is a high-performance, multi-core, lightweight, generic C++98 framework for evolutionary computation. It is intently kept small to stay reliable and understandable.

Sferes2 relies heavily on template-based meta-programming in C++ to get both abstraction and execution speed.

- Partner: UPMC
- Contact: Jean-Baptiste Mouret
- URL: http://github.com/sferes2/sferes2/

6.3. xsensdriver

`xsens_driver`

FUNCTIONAL DESCRIPTION

This is a driver for the third and fourth generation of Xsens IMU devices. The driver is in two parts, a small implementation of most of the MT protocol in Python and a ROS node. It works both on serial and USB interfaces.

These MT* devices can store their configuration and will retrieve it at each boot and then stream data according to this configuration. The node only forwards the data streamed onto ROS topics. In order to configure a device, one can use the mtdevice.py script (or the vendor tool on Windows).

- Contact: Francis Colas
- URL: https://github.com/ethz-asl/ethzasl_xsens_driver

6.4. Platforms

6.4.1. iCub

iCub is a humanoid robot with the size of a 4 years old child. It is developed by the Italian Institute of Technology (Genoa, Italy), which is the coordinator of the EU project CoDyCo. The iCub robot was acquired thanks to the funding of this project.

Our version of iCub has a v2 head, v1 torso, v2.5 legs. It has 6 force/torque sensors, a distributed tactile skin, and inertial sensor in the head.

The robot is used in the context of the projects CoDyCo and Resibots. The software developed for the iCub is mostly published on the github page of our team:

https://github.com/inria-larsen

6.4.2. Pepper

Pepper is a humanoid mobile robot, produced by SoftBank Robotics (formerly Aldebaran). It is designed to engage humans in social interactions, entertain or communicate through gestures and visual animations on its front laptop.

The robot was acquired in the context of the CPER SCIARAT to study human-robot interaction for personal assistance.

7. New Results

7.1. Lifelong Autonomy

7.1.1. PsyPhINe: Cogito Ergo Es

Participant: Amine Boumaza.

PsyPhINe is an interdisciplinary and exploratory project (see 8.1.1) between philosophers, psychologists and computer scientists. The goal of the project is related to cognition and behavior. Cognition is a set of processes that are difficult to unite in a general definition. The project aims to explore the idea of assignments of intelligence or intentionality, assuming that our intersubjectivity and our natural tendency to anthropomorphize play a central role: we project onto others parts of our own cognition. To test these hypotheses, our aim is to design a "non-verbal" Turing Test, which satisfies the definitions of our various fields (psychology, philosophy, neuroscience and computer science) using a robotic prototype. Some of the questions that we aim to answer are: is it possible to give the illusion of cognition and/or intelligence through such a technical device? How elaborate must be the control algorithms or "behaviors" of such a device so as to fool test subjects? How many degrees of freedom must it have?

Last year, an experimental robotic device was designed and built, and an experimental campaign with human subject was conducted. The experiments consisted in recording the interactions of the subjects with the robot when realizing a task. The results of the experiments are under analysis and will partly be presented at the second edition of the PsyPhINe workshop organized by the group, gathering top researchers from philosophy, anthropology, psychology and computer science to discuss and exchange on our methodology (see 9.1.1.1).

7.1.2. Localisation of robots on load-sensing floor

Participants: François Charpillet, Francis Colas, Vincent Thomas.

The use of floor-sensors in ambient intelligence contexts began in the late 1990's. We designed such a sensing floor in Nancy in collaboration with the Hikob company (http://www.hikob.com) and Inria SED. This is a load-sensing floor which is composed of square tiles, each equipped with two ARM processors (Cortex m3 and a8), 4 load cells, and a wired connection to the four neighboring cells. Ninety tiles cover the floor of our experimental platform (HIS).

This year, with Alexis Grall (master student from Enseirb-Matmeca), we have focused on identifying localisation and tracking scenarios involving several robots and on collecting data corresponding to instantiation of these scenarios. These data originated from the sensing tiles but also from Qualisys motion capture system in order to have information about ground-truth. We have also focused on basic algorithms (for instance, Kalman filter) to tackle the issue of tracking targets, but we plan to investigate more elaborate strategies for dealing with sensor discontinuity (for example, when the robot leaves or enters a tile) and multi-traget tracking (Joint Probability Data Association Filter algorithm [52]).

With Mohammad Rami Koujan, we also started to apply deep-learning techniques on those sequential data in order to compare model-based and model-free approaches. This work included some long-term data collection with a randomized behavior in order to have enough training data.

7.1.3. Active sensing and multi-camera tracking

Participants: Olivier Buffet, François Charpillet, Vincent Thomas.

The problem of active sensing is of paramount interest for building self awareness in robotic systems. It consists of a system to make decisions in order to gather information (measured through the entropy of the probability distribution over unknown variables) in an optimal way.

This problem we are focusing on consists of following the trajectories of persons with the help of several controllable cameras in the smart environment. This is a difficult problem since the set of cameras cannot simultaneously cover the whole environment, some persons can be hidden by obstacles or by other persons, and the behavior of each person is governed by internal variables which can only be inferred (such as his motivation or his hunger).

The approach we are working on is based on probabilistic decision processes in partial observability (POMDP - Partially Observable Markov Decision Processes) and particle filters. In the past, we have proposed an original formalism rho-*POMDP* and new algorithms for representing and solving active sensing problems [38] by tracking several persons with fixed camera based on particle filters and Simultaneous Tracking and Activity Recognition approach [45].

This year, we have focused on investigating the issue of solving the active sensing problem with controllable cameras. Approaches based on Monte-Carlo Tree Search algorithms (MCTS) like POMCP [54] are currently investigated for adressing the combinatorial explosion of the state space to consider (which is the space of probability distributions over all the possible states of the system).

7.1.4. Audio Source Localization

Participants: François Charpillet, Francis Colas, Van Quan Nguyen.

We collaborate on this subject with Emmanuel Vincent from the Multispeech team (Inria Nancy - Grand Est).

We considered, here, the task of audio source localization using a microphone array on a mobile robot. Active localization algorithms have been proposed in the literature that can estimate the 3D position of a source by fusing the measurements taken for different poses of the robot. A typical implicit assumption in the literature is that the sound source is active, but a lot of real sound sources are actually intermittent. Systems of activity detection exist but cannot reach perfect accuracy. In this work, we propose a new mixture Kalman filter that explicitly includes the discrete activity of the source in the estimated state vector, alongside the continuous states such as the position of the robot or the sound source. We take into account the imperfection of activity detection systems in order to show that we have better accuracy than the state of the art [26].

This work is led through the PhD Thesis of Van Quan Nguyen under the supervision of Emmanuel Vincent and Francis Colas.

7.1.5. Learning for damage recovery

Participants: Jean-Baptiste Mouret, Konstantinos Chatzilygeroudis, Vassilis Vassiliades, Dorian Goepp.

In 2015, we introduced a novel algorithm that allows robots to learn by trial-and-error when they are damaged [42]. In 2016, we extended this algorithm to make it easier to deploy it in real-life situations and real systems:

- We added "safety constraints" so that the learning algorithm both maximizes the post-damage performance and minimizes the probability of breaking the robot during the learning process; we demonstrated this extension with a simulation of the iCub robot, which is a fragile and expensive robot (around 250,000 euros) for which we would like to use our learning algorithms [33].
- We proposed a novel algorithm that does not require to reset the robot to its starting position between each trial [40], which allows the damaged robots to "learn while doing". We demonstrated this algorithm on our 6-legged walking robot.
- We extended the MAP-Elites algorithm, that is, the evolutionary algorithm that we use to generate prior probability distributions for our online learning algorithm, to scale-up to high-dimensional search spaces [59]. The algorithm is based on central Voronoi tesselations (CVT). In addition, we investigated the influence of the encoding (representation of the controller) on the performance of MAP-Elites [30].

7.1.6. Interactions with biology

Participant: Jean-Baptiste Mouret.

We continued our on-going collaborations with biologists.

- *The Evolutionary Origins of Hierarchy.* Hierarchical organization—the recursive composition of sub-modules—is ubiquitous in biological networks, including neural, metabolic, ecological, and genetic regulatory networks, and in man-made systems such as large organizations and the Internet. In this contribution, we showed that the pressure to minimize the connection costs in network can explain the evolution of hierarchical and modular biological networks [21]; this result extends our previous work on the evolutionary origins of modularity in biological networks [41]. (Collaboration with Jeff Clune, University of Wyoming, USA).
- *Animal-robot interaction.* We worked with a team based in Rennes to perform preliminary experiments about animal-robot attachment (here with a gallinaceous bird) [16].

7.1.7. Learning for whole-body motions

Participants: Serena Ivaldi, Valerio Modugno.

Within the European project CoDyCo, we studied how to combine learning, dynamics, and control for redundant robots. In [25], we proposed a framework to automatically optimize the evolution in time of soft task priorities for multi-task controllers. The motivation of the work was to propose a way to automatate the manual optimization procedure of task priorities and weights, that is classically done by control experts and is time consuming. In [24], we improved the framework by using constrained stochastic optimization algorithms to optimize the task priorities while ensuring that the system constraints (robot and problem setting) are never violated. We showed the results on our robot iCub. Our master student Ugo Chervet contributed to the simulations of this paper.

7.2. Natural Interaction with Robotic Systems

7.2.1. Human Activity recognition on load-sensing floor

Participant: François Charpillet.

In the framework of a collaboration with Lebanese University and CRIStAL laboratory, Lille, we have evaluated this year the capability of the load-sensing floor that we have designed in Nancy, to adress fall detection and activity recognition for elderly people living alone at Home.

The Inria-Nancy sensing floor consists of 104 tiles (60*60 cm). Each tile is equipped with a 3-axis accelerometer in the center of the tile, and four force sensors (strain gauge load cells) positioned at each corner.

The pressure sensors measure the load forces exerted on the floor that can be used to determine, for example, the center of pressure of objects, robots or human beeing on the floor.

This year we have demonstrated that we can also determine the posture or activiy of the monitored person (walking, sitting, standing, falling, etc.) by combining the pressure amount, the pressure duration on a tile, the 3-axis acceleration using a relatively simple algorithm [10], [11].

7.2.2. Human Activity recognition with depth camera

Participants: François Charpillet, Xuan Son Nguyen.

This year, we proposed a new local descriptor for action recognition in depth images. The proposed descriptor relies on surface normals in 4D space of depth, time, spatial coordinates and higher-order partial derivatives of depth values along spatial coordinates. In order to classify actions, we follow the traditional Bag-of-words (BoW) approach, and propose two encoding methods termed Multi-Scale Fisher Vector (MSFV) and Temporal Sparse Coding based Fisher Vector Coding (TSCFVC) to form global representations of depth sequences. The high- dimensional action descriptors resulted from the two encoding methods are fed to a linear SVM for efficient action classification. Our proposed methods are evaluated on two public benchmark datasets, MSRAction3D and MSRGesture3D. The experimental result shows the effectiveness of the proposed methods on both the datasets.

7.2.3. Human Posture Recognition

Participants: François Charpillet, Abdallah Dib, Alain Filbois, Thomas Moinel.

Human pose estimation in realistic world conditions raises multiple challenges such as foreground extraction, background update and occlusion by scene objects. Most of existing approaches were demonstrated in controlled environments. In this work, we propose a framework to improve the performance of existing tracking methods to cope with these problems. To this end, a robust and scalable framework is provided composed of three main stages. In the first one, a probabilistic occupancy grid updated with a Hidden Markov Model used to maintain an up-to-date background and to extract moving persons. The second stage uses component labelling to identify and track persons in the scene. The last stage uses a hierarchical particle filter to estimate the body pose for each moving person. Occlusions are handled by querying the occupancy grid to identify hidden body parts so that they can be discarded from the pose estimation process. We provide a parallel implementation that runs on CPU and GPU at 4 frames per second. We also validate the approach on our own dataset that consists of synchronized motion capture with a single RGB-D camera data of a person performing actions in challenging situations with severe occlusions generated by scene objects. We make this dataset available online (http://www0.cs.ucl.ac.uk/staff/M.Firman/RGBDdatasets/).

7.2.4. Evaluation of control interfaces by non-experts

Participants: Serena Ivaldi, François Charpillet.

In this work, we address the question of user preference for a robotic interface by non-experts (or naive users without training in robotics), after one single evaluation of such an interface on a simple task. This refers to situations when non-experts face the decision of adopting a robot for episodic use (i.e., not a regular continuous use as workers in factories): the ease of use of an interface is crucial for the robot acceptance. We also probe the possible relation between user performance and individual factors. After a focus group study, we chose to compare the robotic arm joystick and a graphical user interface. Then, we studied the user performance and subjective evaluation of the interfaces during an experiment with the robot arm Jaco and 40 healthy adults. Our results show that the user preference for a particular interface does not seem to depend on their performance in using it: for example, many users express their preference for the joystick while they are better performing with the graphical interface. Contrary to our expectations, this result does not seem to relate to the user's individual factors that we evaluate, namely desire for control and negative attitude towards robots.

The preliminary results of this work are published in [23]. A journal paper with the complete results is in preparation. The work was conducted with the master students Sebastian Marichal and Adrien Malaisé.

7.2.5. Robot acceptance and trust

Participant: Serena Ivaldi.

We continued our collaboration with psychologists.

- *Trust as a measure of robot acceptance*: together with the research group of Elisabetta Zibetti (Université de Paris 8), we proposed trust as a main indicator of acceptance in decision-making tasks characterized by perceptual uncertainty (e.g., evaluating the weight of two objects) and socio-cognitive uncertainty (e.g., evaluating which is the most suitable item in a specific context). We measured trust by the participants' conformation to the iCub's answers to specific questions. We found that participants conformed more to the iCub's answers when their decisions were about functional issues than when they were about social issues. Moreover, the few participants conforming to the iCub's answers for social issues also conformed less for functional issues. Trust in the robot's functional knowledge does not thus seem to be a pre-requisite for trust in its social knowledge. Finally, desire for control, attitude towards social influence of robots and type of interaction scenario did not influence the trust in iCub. The results have been published in [13].
- *Acceptance of assistance robots in EHPADs by professional caregivers*: together with Sophie Nertomb (Université de Lorraine), we started a dialogue with professional caregivers to probe their acceptance and positive/negative attitude towards an assistance robot as a collaborator in an EHPAD. From the first focus group, we found that caregivers are rather positive in adopting a robot to get assistance in some daily tasks with the patients, and they would prefer a social robot such as Pepper rather than a functional robot arm, because they believe it could be more useful and would be better accepted by patients. The results of our preliminary investigation were presented in [22].

7.2.6. Individual factors and social/physical signals

Participant: Serena Ivaldi.

We finalized our study about the influence of individual factors in the production of social signals during human-humanoid interaction on a collaborative assembly task. We found that the more people are extrovert, the more and longer they tend to talk with the robot, and the more people have a negative attitude towards robots, the less they will look at the robot face and the more they will look at the robot hands where the assembly and the contacts occur. Our results confirm and provide evidence that the engagement models classically used in human-robot interaction should take into account attitudes and personality traits. The results are published in [15].

We started to study the influence of individual factors on physical signals and collaborative movement. We made interesting observations, for example the influence of age and negative attitude towards robots in the amount of exchanged forces. Part of the analysis was performed by the master student Anthony Voilqué. A paper describing our findings is in preparation.

7.2.7. Learning gait models with cheap sensors for applications in EHPADs

Participants: Serena Ivaldi, François Charpillet, Olivier Rochel.

Thanks to the MITACS-Inria grant, we started a collaboration with Prof. Dana Kulic in University of Waterloo on the topic of learning gait models with cheap sensors. Jamie Waugh, master student, visited us for 3 months to start a data collection protocol where several sensors are used to monitor the human gait under different conditions. The aim is to learn gait parameters with different sensors, such as IMUs and Kinect cameras, and to provide quantitative comparison of the accuracy of the estimation provided by the different sensors. As ground truth, the Qualisys motion capture and the Gaitrite walking mat are used. The final goal of the project is to be able to deliver algorithms for estimating gait based on cheap sensors that could be used on a daily basis in healthcare facilities such as EHPADs.

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. Project PsyPhINe: Cogitamus ergo sumus

Participant: Amine Boumaza.

This project is financed for two years by the MSH Lorraine (USR3261) gathering researchers from the following institutes: , InterPsy (EA 4432), APEMAC, EPSaM (EA4360), Archives Henri-Poincaré (UMR7117), Inria Bordeaux Sud-Ouest, Loria (UMR7503). Refer to sec. 7.1.1 for further information.

8.1.2. AME Satelor

Participants: François Charpillet, Xuan Son Nguyen, Thomas Moinel, Mélanie Lelaure.

Economic mobilisation agency in Lorraine has launched a new project Satelor providing it with 2.5 million Euros of funding over 3 years, out of an estimated total of 4.7 million. The leader of the project is Pharmagest-Diatelic. Pharmagest, in Nancy, is the French leader in computer systems for pharmacies, with a 43.5 % share of the market, 9,800 clients and more than 700 employees. Recently, the Pharmagest Group expanded its activities into e-health and the development of telemedicine applications. The Satelor project will accompany the partners of the project in developing services for maintaining safely elderly people with loss of autonomy at home or people with a chronic illness. Larsen team will play an important role for bringing some research results such as:

- developing a low cost environmental sensor for monitoring the daily activities of elderly people at home
- developing a low cost sensor for fall detection
- developing a low cost companion robot able to interact with people and monitoring their activities while detecting emergency situations.
- developing a general toolbox for data-fusion: Bayesian approach.

8.2. National Initiatives

8.2.1. PIA LAR Living Assistant Robot

Participants: François Charpillet, Abdallah Dib.

Partners : Crédit Agricole, Diatelic, Robosoft
The LAR project has the objective to design an assistant robot to improve the autonomy and quality of life for elderly and fragile persons. The project started at the beginning of 2015. The role of the Larsen Team is to develop a simultaneous localisation and mapping algorithm using a RGB-D camera. The main issue is to develop an algorithm able to deal with a dynamic environment. Another issue is for the robot to be able to behave with acceptable social skills.

8.3. European Initiatives

8.3.1. FP7 & H2020 Projects

8.3.1.1. RESIBOTS

Title: Robots with animal-like resilience

Programm: H2020

Type: ERC

Duration: May 2015 - April 2020

Coordinator: Inria

Inria contact: Jean Baptiste Mouret

Despite over 50 years of research in robotics, most existing robots are far from being as resilient as the simplest animals: they are fragile machines that easily stop functioning in difficult conditions. The goal of this proposal is to radically change this situation by providing the algorithmic foundations for low-cost robots that can autonomously recover from unforeseen damage in a few minutes. The current approach to fault tolerance is inherited from safety-critical systems (e.g. spaceships or nuclear plants). It is inappropriate for low-cost autonomous robots because it relies on diagnostic procedures, which require expensive proprioceptive sensors and contingency plans, which cannot cover all the possible situations that an autonomous robot can encounter. It is here contended that trial-and-error learning algorithms provide an alternate approach that does not require diagnostic or pre-defined contingency plans. In this project, we will develop and study a novel family of such learning algorithms that make it possible for autonomous robots to quickly discover compensatory behaviors. We will thus shed a new light on one of the most fundamental questions of robotics: how can a robot be as adaptive as an animal? The techniques developed in this project will substantially increase the lifespan of robots without increasing their cost, and will open new research avenues for adaptive machines.

8.3.1.2. CoDyCo

Participants: Serena Ivaldi, Valerio Modugno, Oriane Dermy.

Title: Whole-body Compliant Dynamical Contacts in Cognitive Humanoids

Program: FP7

Instrument: STREP

Objective: Cognitive Systems and Robotics (b)

Duration: March 2013 - February 2017 (4 years)

Coordinator: Francesco Nori (Italian Institute of Technology)

Partners: TU Darmstadt (Germany), Université Pierre et Marie Curie (France), Josef Stefan Institue (Slovenia), University of Birmingham (UK)

Inria contact: Serena Ivaldi

Abstract: The aim of CoDyCo is to advance the current control and cognitive understanding of robust, goal-directed whole-body motion interaction with multiple contacts. CoDyCo will go beyond traditional approaches by: (1) proposing methodologies for performing coordinated interaction tasks with complex systems; (2) combining planning and compliance to deal with predictable and unpredictable events and contacts; (3) validating theoretical advances in real-world interaction scenarios. First, CoDyCo will advance the state-of-the-art in the way robots coordinate physical interaction and physical mobility. Traditional industrial applications involve robots with limited mobility. Consequently, interaction (e.g., manipulation) has been treated separately from whole-body posture (e.g., balancing), assuming the robot firmly connected to the ground. Foreseen applications involve robots with augmented autonomy and physical mobility. Within this novel context, physical interaction influences stability and balance. To allow robots to surpass barriers between interaction and posture control, CoDyCo will be grounded in principles governing whole-body coordination with contact dynamics. Second, CoDyCo will go beyond traditional approaches in dealing with all perceptual and motor aspects of physical interaction, unpredictability included. Recent developments in compliant actuation and touch sensing allow safe and robust physical interaction from unexpected contact including humans. The next advancement for cognitive robots, however, is the ability not only to cope with unpredictable contact, but also to exploit predictable contact in ways that will assist in goal achievement. Third, the achievement of the project objectives will be validated in real-world scenarios with the iCub humanoid robot engaged in whole-body goal-directed tasks. The evaluations will show the iCub exploiting rigid supportive contacts, learning to compensate for compliant contacts, and utilizing assistive physical interaction.

8.4. International Initiatives

8.4.1. Participation in Other International Programs

Serena Ivaldi, in collaboration with Prof. Dana Kulic of University of Waterloo, obtained a MITACS-Inria grant for the master student Jamie Waugh for the project "learning gait models".

8.5. International Research Visitors

8.5.1. Visits of International Scientists

- Francesco Nori, researcher at the Italian Institute of Technology, and coordinator of the European Project CoDyCo (where we are partners), visited our team for one month. During this visit, we wrote together a proposal for a H2020 project that was submitted in April 2016 and was subsequently accepted: the project, AnDy, will start in January 2017.
- John Rieffel, Associate Professor at Union College (NY, USA), visited our team for a month. During his visit, we used Bayesian optimization to learn gaits for a soft tensegrity robot. A paper has been submitted.

8.5.1.1. Internships

- Jamie Waugh, master student of University of Waterloo, visited our team for 3 months (from September to December) thanks to a MITACS-Inria grant.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. Member of the Organizing Committees

- Amine Boumaza co-organized "Projections, Interactions, Emotions - Journées PsyPhINe 2016", the second workshop of the PsyPhINe project (http://poincare.univ-lorraine.fr/fr/manifestations/psyphine-2016).
- François Charpillet co-organized and co-chaired the Workshop on On-line decision-making in multi-robot coordination, June 19, 2016, Ann Arbor, Michigan, USA, organized in conjuction of the 2016 Robotics: Science and Systems Conference (RSS 2016).
- Serena Ivaldi co-organized the Workshop "Human-Robot collaboration: towards co-adaptive learning though semi-autonomy and shared control" at IROS 2016 (http://www.ausy.tu-darmstadt.de/Workshops/IROS2016).

9.1.2. Scientific Events Selection

9.1.2.1. Member of the Conference Program Committees

- Amine Boumaza was a PC member of GECCO'2016 (Genetic and Evolutionary Computation Conference), ALIFE'2016 (International Conference on the Synthesis and Simulation of Living Systems), CEC'2016 (Congress on Evolutionary computation).
- Francis Colas was a Technical PC member for the EAI International Conference Track on Smart Cities and the Future Internet (SCiFI).
- Serena Ivaldi was an Associate Editor for the 2016 IEEE/RAS International Conference on Robotics and Automation (ICRA), the 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), the 2016 IEEE/RAS International Conference on Humanoid Robots (HUMANOIDS), the 2016 IEEE International Conference on Development and Learning (ICDL).
- Jean-Baptiste Mouret was a PC member of GECCO'2016 (Genetic and Evolutionary Computation Conference), ALIFE'2016 (International Conference on the Synthesis and Simulation of Living Systems), EVO*2016 (EvoStar), SAB'2016 (Conference on System and Adaptive Behaviors – from animals to animats).
- Vincent Thomas was a member of the program committee for “Journées Francophones sur la Planification la Décision et l'Apprentissage pour la conduite de systèmes 2016” (JFPDA 2016).

9.1.2.2. Reviewer

- François Charpillet was a reviewer for the 2016 IEEE International Conference on Robotics and Automation (ICRA), The 2016 europeen conference on artificial intelligence (ECAI), Rob&IA2016, RFP-IA 2016, WACAI2016, DEMUR, and the 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).
- Francis Colas was a reviewer for the 2016 IEEE International Conference on Robotics and Automation (ICRA), the EAI International Conference on Smart Cities and the Future Internet (SCiFI), and the 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).
- Serena Ivaldi was a reviewer for the ACM International Conference on Human-Robot Interaction (HRI), the IEEE International Conference on Human-Robot Communication (RO-MAN), the International Conference Robotics: Science and Systems (RSS).
- Jean-Baptiste Mouret was a reviewer for the 2016 IEEE International Conference on Robotics and Automation (ICRA), and the 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).
- Vincent Thomas was a reviewer for “Journées Francophones sur la Planification la Décision et l'Apprentissage pour la conduite de systèmes 2016” (JFPDA 2016).

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

- Serena Ivaldi is an editorial board member for the Journal "Intelligent Service Robotics", Springer. She was also Guest Editor for Springer Autonomous Robots for the Special Issue “Whole-body control of contacts and dynamics for humanoid robots”.

9.1.3.2. Reviewer - Reviewing Activities

- Amine Boumaza is a Review Editor for Frontiers in AI and Robotics.
- Francis Colas was a reviewer for the Journal of Field Robotics, and the IEEE Transactions on Automation Science and Engineering.
- Serena Ivaldi was a Review Editor and reviewer for Frontiers in AI and Robotics, and a reviewer for IEEE Transactions on Cognitive and Developmental Systems.
- Jean-Baptiste Mouret is Review Editor for Frontiers in AI and Robotics. He was a reviewer for Nature Communications, Frontiers in Neurobotics, Artificial Life.
- Vincent Thomas was a reviewer for the IEEE Transactions on Cybernetics.

9.1.4. Invited Talks

- Jean-Baptiste Mouret was invited to talk at:
  The Origins Workshop (Arizona State University, USA),
  The cross-disciplinary symposium on Machine Learning and Architecture (Copenhague, Danemark),
  9th SIG on Design Theory of the International Design Society (Keynote, Paris, France),
  Journée des Jeunes Chercheuses et Chercheurs organisée de l'ANR (Paris, France),
  Ministère des finances (Conseil Général de l'Economie / mission de réflexion sur les armes autonomes, Paris, France),
  Journée "Apprentissage et IA" organized by CERNA (Commission de réflexion sur l'Éthique de la Recherche en sciences et technologies du Numérique d'Allistene),
  Journée Scientifiques Inria (Rennes, France),
  Journée Intelligence Artificielle et Voiture Autonomes (Institut VEDECOM, Versailles, France),
  HLR 2016 (German-French Winter School on Humanoids and Legged robots).
- Serena Ivaldi gave the following invited talks:
  06/2016: *Humanoid robotics and human-robot interaction*. Invited talk at Journée Robotique et IA, RFIA 2016, by Olivier Simonin.
  10/2016: *Grasping, vision and interaction for object manipulation with iCub*. Invited talk at IEEE-RAS IROS 2016 Workshop on Grasping and Manipulation, by Yasemin Bekiroglu.
  11/2016: *Exploiting tactile information for whole-body dynamics, learning and human-robot interaction*. Invited talk at IEEE-RAS Humanoids 2016 Workshop on Tactile Manipulation, by Qiang Li.
  11/2016: *Studying human behavior during human-robot collaborative tasks*. Invited talk at IEEE-RAS Humanoids 2016 Workshop on Human Movement Understanding, by Emel Demircan.
  11/2016: *Les robots humanoides: de l'acceptabilité à l'interaction*. Invited talk at the Forum de Sciences Cognitives, Nancy, by Christine Bourjot.
  12/2016: *Learning and interaction with iCub*. Invited talk at the German-French Conference on Humanoid and Legged Robots 2016, by Olivier Stasse.

9.1.5. Leadership within the Scientific Community

- Jean-Baptiste Mouret is the chair of the "evo-devo-robot" task force of the IEEE technical committee "Developmental and Cognitive Systems".

9.1.6. Scientific Expertise

- Serena Ivaldi was appointed vice-president of the CES 33 panel Interaction and Robotics of the ANR. She was an invited member of the CNRS for the "Groupe de Discussion pour le renouvellement de la liste des candidats" section 07 CNRS (Specif Campus, GRETSI & Club EEA) - invited by Specif Campus, 2016.

9.1.7. Research Administration

- Amine Boumaza is a board member of the Évolution Artificielle association.
- Serena Ivaldi was member of the hiring committees:
  - CNRS: Committee member for jury n.29 - IR2 - BAP, sept.-oct. 2016.
  - Maitre de conference: Committee member for jury 27MCF1744 (4335) at UPMC, Paris, apr.-may 2016.
- Francis Colas was member of the hiring committee 27-MCF-0762 at ESSTIN, Université de Lorraine.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

- Master: Karim Bouyarmane, “Programmation C/C++”, 20h eq. TD, M1/M2, ESSTIN, France.
- Master: Francis Colas, “Robotique Autonome”, 18h eq. TD, M2 “Systèmes Interactifs et Robotiques”, CentraleSupélec, France.
- Master: Francis Colas, “Introduction à ROS”, 6h eq. TD, M1, Mines de Nancy, France.
- Master: Serena Ivaldi, “Analyse du comportement”, 15h eq. TD, M2 “Science Cognitive”, Université de Lorraine, France.
- Master: Jean-Baptiste Mouret, “Disruptive technologies: Robotics”, 3h eq. TD, M2 (School of Public Affairs), Sciences Po Paris, France.
- Master: Vincent Thomas, “Modèles probabilistes et Apprentissage par renforcement”, 15h eq. TD, M2 “Informatique - Image Perception Raisonnement Cognition”, Univ. Lorraine, France.
- Master: Vincent Thomas, “Game Design”, 20h eq. TD, M1 “Sciences Cognitives”, Univ. Lorraine, France.
- Master: Vincent Thomas, “Agent intelligents et collectifs”, 20h eq. TD, M1 “Sciences Cognitives”, Univ. Lorraine, France.
- Master: Vincent Thomas, “Serious Game”, 12h eq. TD, M2 “Sciences Cognitives”, Univ. Lorraine, France.

9.2.2. Supervision

- PhD: Abdallah Dib, “*Assistance à la personne en perte d’autonomie : étude de l’apport d’un robot compagnon*”, 24 May 2016, François Charpillet (advisor).
- PhD in progress: Adrian Bourgaud, “*Multi-sensor Fusion and Active Sensing*”, started in Jul. 2015, François Charpillet (advisor).
- PhD in progress: Konstantinos Chatzilygeroudis, “*Diagnosis-free Damage Recovery in Robotics with Machine Learning*”, started in Oct. 2015, Jean-Baptiste Mouret (advisor).
- PhD in progress: Oriane Dermy, “*Learning to control the physical interaction of a humanoid robot with humans*”, started in Nov. 2015, François Charpillet (advisor), Serena Ivaldi.
- PhD in progress: Yassine El Khadiri, “Apprentissage automatique pour l’assistance à l’autonomie à domicile”, started in Nov. 2016, François Charpillet (advisor).
- PhD in progress: Iñaki Fernández Pérez, “*Apprentissage incrémental évolutionnaire*”, started in Oct. 2013, F. Charpillet (advisor), Amine Boumaza.
- PhD in progress: Nassim Kaldé, “*Exploration et reconstruction d’un environnement inconnu par une flottille de robots*”, started in Oct. 2012, François Charpillet (advisor), Olivier Simonin.
- PhD in progress: Rituraj Kaushik, “Fast adaptation to damage by exploiting trajectory data”, started in Oct. 2016, Jean-Baptiste Mouret (advisor).
- PhD in progress: Van Quan Nguyen, “Mapping of a sound environment by a mobile robot”, started in Dec. 2014, Emmanuel Vincent (advisor), Francis Colas, François Charpillet.

9.2.3. Juries

- François Charpillet was reviewer and member of the PhD committee of :
  - Hendry Ferreira Chame, “Egocentric Representations for Autonomous Navigation of Humanoïd Robots”, école centrale de Nantes, IRCCYN.
  - Patrick Béchon, “Planification multi-robot pour des missions de surveillance avec contraintes de communication”, Université de Toulouse, ISAE, LAAS, ONERA.
  - Raphael Lallemand, “Symbolic and Geometric Planning for teams of Robots and Humans”, Université de Toulouse, INSA Toulouse, LAAS.
  - Loïc Sevrin, “Mesure et suivi d’activité de plusieurs personnes dans un Living Lab en vue de l’extraction d’indicateurs de santé et de bien être”, Université de Claude Bernard Lyon 1, Institut des nanotechnologies de Lyon;

  - Vishnu Karakkat Narayanan, “Characterizing assistive shared control through vision-based and human-aware designs for wheelchair navigation assistance”, Université Bretagne Loire, INSA Rennes, Team Project Lagatic and Chroma.
  - Haïfa Rabai, “Réseau dynamique d’applications chaotiques couplées pour l’étude de la mobilité urbaine”, Université du Havre.
- François Charpillet was member and chair of the PhD committee of :
  - Coralie Angeletti, “Stratégie de Perception Active pour l’Interprétation de Scènes”, University Blaise Pascal, Clermont Ferrand.
  - Kevin Roussel, “Évaluation et amélioration des plates-formes logicielles pour réseaux de capteurs sans-fil, pour optimiser la qualité de service et l’énergie”, Université de Lorraine.
- François Charpillet was member of the Phd committee of :
  - Abdallah Dib, “Vers un système de capture du mouvement humain en 3D pour un robot mobile évoluant dans un environnement encombré”, Lorraine University.
  - Seifallah Ben Saad, “Conception d’un algorithme de coordination hybride de groupes de robots sous-marins communicants Application : acquisition optique systématique et détaillée des fonds marins”, Université de bretagne occidentale, ENSTA Bretagne.

9.3. Popularization

- Amine Boumaza is a member of the editorial board of “Interstice”.
- Vincent Thomas gave proposed tutorials on “physics simulation” and “reinforcement learning” during “journées ISN-EPI” (24th of Mars 2016).
- Vincent Thomas participated in the preparation of “Computer Science Exporoute” (conducted by Inria Nancy Grand-Est) planned for 2017.
- Jean-Baptiste Mouret wrote an article for “Interstices” (“ Des robots qui s’adaptent aux dommages en seulement quelques minutes”).
- Jean-Baptiste Mouret helped Pierre Vandeginste (journalist) to write an article about his work in “La Recherche” (Dec. 2016); he also appeared in Science et Avenir, Arte Future Mag, Socialter, Telerama.
- Serena Ivaldi appeared in the following articles / gave the following interviews:
  07/2016: Humanité Dimanche, Homme/robot. Le trouble au rendez-vous. http://www.humanite.fr/hommerobot-le-trouble-au-rendez-vous-612149
  06/2016: Inriality, Robots humanoides : une inquiétante étrangeté. http://www.inriality.fr/culture-loisirs/relations-homme-robot/robophobie/robots-humanoides-une/
  06/2016: Les Inrockuptibles, n.1070, Comment les robots ont conquis nos coeurs. http://www.lesinrocks.com/2016/06/01/actualite/dossier-high-tech-androides-ont-conquis-coeurs-11832819/
  03/2016: Interstices, Des robots au service de l’homme. https://interstices.info/jcms/p_88305/des-robots-au-service-des-hommes
  03/2016: La semaine, Têtes chercheuses. http://www.lasemaine.fr/2016/03/17/tetes-chercheuses
  03/2016: Pour la science, Quels obstacles à l’insertion des robots en société ? https://pbs.twimg.com/media/CceuEH3W4AEoNx-.jpg:large

10. Bibliography

Major publications by the team in recent years

[1] M. Araya-López, O. Buffet, V. Thomas, F. Charpillet.*A POMDP Extension with Belief-dependent Rewards*, in "Neural Information Processing Systems - NIPS 2010", Vancouver, Canada, Advances in Neural Information Processing Systems 23, MIT Press, December 2010, https://hal.inria.fr/inria-00535560.

[2] A. CULLY, J. CLUNE, D. TARAPORE, J.-B. MOURET.*Robots that can adapt like animals*, in "Nature", May 2015, vol. 521, n^o^ 7553, p. 503-507 [*DOI :* 10.1038/NATURE14422], https://hal.archives-ouvertes.fr/hal-01158243.

[3] S. IVALDI, S. LEFORT, J. PETERS, M. CHETOUANI, J. PROVASI, E. ZIBETTI.*Towards engagement models that consider individual factors in HRI: on the relation of extroversion and negative attitude towards robot to gaze and speech during a human-robot assembly task*, in "International Journal of Social Robotics", June 2016, to appear (provisional acceptance), http://arxiv.org/abs/1508.04603.

[4] F. POMERLEAU, F. COLAS, R. SIEGWART.*A Review of Point Cloud Registration Algorithms for Mobile Robotics*, in "Foundations and Trends in Robotics (FnTROB)", 2015, vol. 4, n^o^ 1, p. 1–104 [*DOI :* 10.1561/2300000035], https://hal.archives-ouvertes.fr/hal-01178661.

[5] O. SIMONIN, F. CHARPILLET, E. THIERRY.*Revisiting wavefront construction with collective agents: an approach to foraging*, in "Swarm Intelligence", June 2014, vol. 8, n^o^ 2, p. 113-138 [*DOI :* 10.1007/S11721-014-0093-3], https://hal.inria.fr/hal-00974068.

Publications of the year

Doctoral Dissertations and Habilitation Theses

[6] A. DIB.*Toward a motion capture system in 3D for a mobile robot moving in a cluttered environment*, Université de Lorraine, May 2016, https://hal.inria.fr/tel-01333772.

Articles in International Peer-Reviewed Journal

[7] M. AMBLARD, A. BOUMAZA.*Human Robots, Are You Real Then?*, in "Iride", 2016, vol. XXIX, n^o^ 2, p. 287-298 [*DOI :* 10.1414/84251], https://hal.inria.fr/hal-01391754.

[8] P. BESSIÈRE, J. DIARD, F. COLAS.*Modèles probabilistes formels pour problèmes cognitifs usuels*, in "Intellectica - La revue de l'Association pour la Recherche sur les sciences de la Cognition (ARCo)", June 2016, vol. 65, n^o^ 1, p. 111-141, https://hal.archives-ouvertes.fr/hal-01345697.

[9] A. CULLY, J.-B. MOURET.*Evolving a Behavioral Repertoire for a Walking Robot*, in "Evolutionary Computation", 2016, vol. 24, n^o^ 1, 33 [*DOI :* 10.1162/EVCO_A_00143], https://hal.inria.fr/hal-01095543.

[10] M. DAHER, A. DIAB, M. EL BADAOUI EL NAJJAR, M. KHALIL, F. CHARPILLET.*Automatic Fall Detection System using Sensing Floors*, in "International Journal of Computing and Information Sciences (IJCIS)", December 2016, vol. 12, n^o^ 1, p. 75-82 [*DOI :* 10.21700/IJCIS.2016.110], https://hal.archives-ouvertes.fr/hal-01393478.

[11] M. DAHER, A. DIAB, M. EL BADAOUI EL NAJJAR, M. KHALIL, F. CHARPILLET.*Elder Tracking and Fall Detection System using Smart Tiles*, in "IEEE Sensors Journal", December 2016 [*DOI :* 10.1109/JSEN.2016.2625099], https://hal.archives-ouvertes.fr/hal-01393492.

[12] 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.

[13] I. GAUDIELLO, E. ZIBETTI, S. LEFORT, M. CHETOUANI, S. IVALDI.*Trust as indicator of robot functional and social acceptance. An experimental study on user conformation to iCub answers*, in "Computers in Human Behavior", 2016 [*DOI :* 10.1016/J.CHB.2016.03.057], https://hal.inria.fr/hal-01298502.

[14] S. IVALDI, J. BABIČ, M. MISTRY, R. MURPHY.*Special Issue on Whole-body control of contacts and dynamics for humanoid robots*, in "Autonomous Robots", January 2016 [*DOI :* 10.1007/S10514-016-9545-5], https://hal.archives-ouvertes.fr/hal-01258282.

[15] S. IVALDI, S. LEFORT, J. PETERS, M. CHETOUANI, J. PROVASI, E. ZIBETTI.*Towards engagement models that consider individual factors in HRI: on the relation of extroversion and negative attitude towards robots to gaze and speech during a human-robot assembly task : Experiments with the iCub humanoid robot*, in "International Journal of Social Robotics", 2016 [*DOI :* 10.1007/S12369-016-0357-8], https://hal.inria.fr/hal-01322231.

[16] L. JOLLY, F. PITTET, J.-P. CAUDAL, J.-B. MOURET, C. HOUDELIER, S. LUMINEAU, E. DE MARGERIE.*Animal-to-robot social attachment: initial requisites in a gallinaceous bird*, in "Bioinspiration and Biomimetics", 2016, vol. 11, n^{o} 1, 016007 [*DOI :* 10.1088/1748-3190/11/1/016007], https://hal-univ-rennes1.archives-ouvertes.fr/hal-01274231.

[17] H. MENGISTU, J. HUIZINGA, J.-B. MOURET, J. CLUNE.*The Evolutionary Origins of Hierarchy*, in "PLoS Computational Biology", 2016, vol. 12, n^{o} 6, 23 [*DOI :* 10.1371/JOURNAL.PCBI.1004829.S021], https://hal.inria.fr/hal-01330681.

[18] J.-B. MOURET.*Micro-Data Learning: The Other End of the Spectrum*, in "ERCIM News", September 2016, n^{o} 107, 2, https://hal.inria.fr/hal-01374786.

[19] V. PADOIS, S. IVALDI, J. BABIČ, M. MISTRY, J. PETERS, F. NORI.*Whole-body multi-contact motion in humans and humanoids: Advances of the CoDyCo European project*, in "Robotics and Autonomous Systems", 2016 [*DOI :* 10.1016/J.ROBOT.2016.08.017], https://hal.archives-ouvertes.fr/hal-01399360.

International Conferences with Proceedings

[20] A. D. FAVA, K. BOUYARMANE, K. CHAPPELLET, E. RUFFALDI, A. KHEDDAR.*Multi-Contact Motion Retargeting from Human to Humanoid Robot*, in "IEEE-RAS International Conference on Humanoid Robots", Cancun, Mexico, Proceedings of the IEEE-RAS International Conference on Humanoid Robots, November 2016, https://hal.archives-ouvertes.fr/hal-01414986.

[21] J. HUIZINGA, J.-B. MOURET, J. CLUNE.*Does Aligning Phenotypic and Genotypic Modularity Improve the Evolution of Neural Networks?*, in "Proceedings of the 25th Genetic and Evolutionary Computation Conference (GECCO)", Denver, France, ACM, 2016, p. 125 - 132 [*DOI :* 10.1145/2908812.2908836], https://hal.inria.fr/hal-01402502.

[22] A. MALAISÉ, S. NERTOMB, F. CHARPILLET, S. IVALDI.*Towards collaboration between professional caregivers and robots - A preliminary study*, in "International Conference on Social Robotics - Workshop “Using social robots to improve the quality of life in the elderly”", Kansas City, United States, November 2016, https://hal.inria.fr/hal-01377708.

[23] S. MARICHAL, A. MALAISÉ, V. MODUGNO, O. DERMY, F. CHARPILLET, S. IVALDI.*One-shot Evaluation of the Control Interface of a Robotic Arm by Non-Experts*, in "International Conference on Social Robotics", Kansas City, United States, November 2016, https://hal.inria.fr/hal-01353809.

[24] V. MODUGNO, U. CHERVET, G. ORIOLO, S. IVALDI.*Learning soft task priorities for safe control of humanoid robots with constrained stochastic optimization*, in "IEEE-RAS International Conference on Humanoid Robots (HUMANOIDS)", Cancun, Mexico, November 2016, https://hal.inria.fr/hal-01377690.

[25] V. MODUGNO, G. NEUMANN, E. RUECKERT, G. ORIOLO, J. PETERS, S. IVALDI.*Learning soft task priorities for control of redundant robots*, in "IEEE International Conference on Robotics and Automation (ICRA 2016)", Stockholm, Sweden, May 2016, https://hal.archives-ouvertes.fr/hal-01273409.

[26] V. Q. NGUYEN, F. COLAS, E. VINCENT, F. CHARPILLET.*Localizing an Intermittent and Moving Sound Source Using a Mobile Robot*, in "International Conference on Intelligent Robots and Systems (IROS)", Deajeon, South Korea, October 2016, https://hal.archives-ouvertes.fr/hal-01354006.

[27] X. S. NGUYEN, T. P. NGUYEN, F. CHARPILLET.*Effective Surface Normals Based Action Recognition in Depth Images*, in "ICPR 2016 - 23rd International Conference on Pattern Recognition", Cancun, Mexico, December 2016, https://hal.inria.fr/hal-01409021.

[28] X. S. NGUYEN, T. P. NGUYEN, F. CHARPILLET.*Improving Surface Normals Based Action Recognition in Depth Images*, in "13th International Conference on Advanced Video and Signal-Based Surveillance", Colorado Springs, United States, August 2016, https://hal.inria.fr/hal-01409043.

[29] M. RIO, F. COLAS, M. ANDRIES, F. CHARPILLET.*Probabilistic sensor data processing for robot localization on load-sensing floors*, in "IEEE International Conference on Robotics and Automation (ICRA)", Stockholm, Sweden, May 2016, https://hal.inria.fr/hal-01274696.

[30] D. TARAPORE, J. CLUNE, A. CULLY, J.-B. MOURET.*How Do Different Encodings Influence the Performance of the MAP-Elites Algorithm?*, in "Genetic and Evolutionary Computation Conference", Denver, United States, 2016 [*DOI :* 10.1145/2908812.2908875], https://hal.inria.fr/hal-01302658.

[31] S. WANG, F. COLAS, M. LIU, F. MONDADA, S. MAGNENAT.*Localization of inexpensive robots with low-bandwidth sensors*, in "13th International Symposium on Distributed Autonomous Robotic Systems", London, United Kingdom, November 2016, https://hal.inria.fr/hal-01379218.

Conferences without Proceedings

[32] K. CHATZILYGEROUDIS, A. CULLY, J.-B. MOURET.*Towards semi-episodic learning for robot damage recovery*, in "Workshop on AI for Long-Term Autonomy at the IEEE International Conference on Robotics and Automation (ICRA)", Stockholm, Sweden, Lars Kunze and Nick Hawes and Tom Duckett and Gabe Sibley, May 2016, https://hal.inria.fr/hal-01376288.

[33] V. PAPASPYROS, K. CHATZILYGEROUDIS, V. VASSILIADES, J.-B. MOURET.*Safety-Aware Robot Damage Recovery Using Constrained Bayesian Optimization and Simulated Priors*, in "Bayesian Optimization: Black-box Optimization and Beyond (workshop at NIPS)", Barcelone, France, 2016, https://hal.inria.fr/hal-01407757.

Research Reports

[34] A. BOURGAUD, F. CHARPILLET.*A HMM Classifier with Contextual Observability: Application to Indoor People Tracking*, LORIA - Université de Lorraine, January 2016, https://hal.archives-ouvertes.fr/hal-01323792.

Scientific Popularization

[35] S. IVALDI, J. JONGWANE.*Des robots au service des hommes*, in "Interstices", March 2016, https://hal.inria.fr/hal-01350455.

[36] J.-B. MOURET, A. CULLY.*Des robots qui s'adaptent aux dommages en seulement quelques minutes*, in "Interstices", October 2016, https://hal.inria.fr/hal-01412441.

References in notes

[37] M. ANDRIES, F. CHARPILLET.*Multi-robot taboo-list exploration of unknown structured environments*, in "2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2015)", Hamburg, Germany, September 2015, https://hal.inria.fr/hal-01196008.

[38] M. ARAYA-LÓPEZ, O. BUFFET, V. THOMAS, F. CHARPILLET.*A POMDP Extension with Belief-dependent Rewards*, in "Neural Information Processing Systems - NIPS 2010", Vancouver, Canada, Advances in Neural Information Processing Systems 23, MIT Press, December 2010, https://hal.inria.fr/inria-00535560.

[39] T. BARFOOT, J. KELLY, G. SIBLEY.*Special Issue on Long-Term Autonomy*, in "The International Journal of Robotics Research", 2013, vol. 32, n^{o} 14, p. 1609–1610.

[40] K. CHATZILYGEROUDIS, V. VASSILIADES, J.-B. MOURET.*Reset-free Trial-and-Error Learning for Data-Efficient Robot Damage Recovery*, in "arXiv:1610.04213", 2016.

[41] J. CLUNE, J.-B. MOURET, H. LIPSON.*The evolutionary origins of modularity*, in "Proc. R. Soc. B", The Royal Society, 2013, vol. 280, n^{o} 1755, 20122863.

[42] A. CULLY, J. CLUNE, D. TARAPORE, J.-B. MOURET.*Robots that can adapt like animals*, in "Nature", May 2015, vol. 521, n^{o} 7553, p. 503-507 [*DOI :* 10.1038/NATURE14422], https://hal.archives-ouvertes.fr/hal-01158243.

[43] A. DEL PRETE, F. NORI, G. METTA, L. NATALE.*Prioritized Motion-Force Control of Constrained Fully-Actuated Robots: "Task Space Inverse Dynamics"*, in "Robotics and Autonomous Systems", 2014, http://dx.doi.org/10.1016/j.robot.2014.08.016.

[44] A. DIB, F. CHARPILLET.*Pose Estimation For A Partially Observable Human Body From RGB-D Cameras*, in "IEEE/RJS International Conference on Intelligent Robots and Systems (IROS)", Hamburg, Germany, September 2015, 8, https://hal.inria.fr/hal-01203638.

[45] A. FANSI TCHANGO, V. THOMAS, O. BUFFET, F. FLACHER, A. DUTECH.*Simultaneous Tracking and Activity Recognition (STAR) using Advanced Agent-Based Behavioral Simulations*, in "ECAI - Proceedings of the Twenty-first European Conference on Artificial Intelligence", Pragues, Czech Republic, August 2014, https://hal.inria.fr/hal-01073424.

[46] I. FERNÁNDEZ PÉREZ, A. BOUMAZA, F. CHARPILLET.*Comparison of Selection Methods in On-line Distributed Evolutionary Robotics*, in "ALIFE 14: The fourteenth international conference on the synthesis and simulation of living systems", New York, United States, Artificial Life 14, July 2014 [*DOI :* 10.7551/978-0-262-32621-6-CH046], https://hal.inria.fr/hal-01091119.

[47] U. FRESE.*Interview: Is SLAM Solved?*, in "KI - Künstliche Intelligenz", 2010, vol. 24, n° 3, p. 255-257, http://dx.doi.org/10.1007/s13218-010-0047-x.

[48] J. KOBER, J. A. BAGNELL, J. PETERS.*Reinforcement Learning in Robotics: A Survey*, in "The International Journal of Robotics Research", August 2013.

[49] S. KOOS, A. CULLY, J.-B. MOURET.*Fast damage recovery in robotics with the t-resilience algorithm*, in "The International Journal of Robotics Research", 2013, vol. 32, n° 14, p. 1700–1723.

[50] F. POMERLEAU, P. KRÜSI, F. COLAS, P. FURGALE, R. SIEGWART.*Long-term 3D map maintenance in dynamic environments*, in "Robotics and Automation (ICRA), 2014 IEEE International Conference on", IEEE, 2014, p. 3712–3719.

[51] SPARC.*Robotics 2020 Multi-Annual Roadmap*, 2014, http://www.eu-robotics.net/ppp/objectives-of-our-topic-groups/.

[52] S. SAEED, M. MOHAMMAD BAGHER, G. D. ALIAKBAR.*Multiple Target Tracking for Mobile Robots Using the JPDAF Algorithm*, in "2007 19th IEEE International Conference on Tools with Artificial Intelligence", IEEE Computer Society, 2007, vol. 01, p. 137-145.

[53] J. SHAH, J. WIKEN, B. WILLIAMS, C. BREAZEAL.*Improved human-robot team performance using Chaski, A human-inspired plan execution system*, in "ACM/IEEE International Conference on Human-Robot Interaction (HRI)", 2011, p. 29-36.

[54] D. SILVER, J. VENESS.*Monte-Carlo Planning in Large POMDPs*, in "Advances in Neural Information Processing Systems 23", Curran Associates, Inc., 2010, p. 2164–2172.

[55] O. SIMONIN, T. HURAUX, F. CHARPILLET.*Interactive Surface for Bio-inspired Robotics, Re-examining Foraging Models*, in "23rd IEEE International Conference on Tools with Artificial Intelligence (ICTAI)", Boca Raton, United States, IEEE, November 2011, https://hal.inria.fr/inria-00617155.

[56] N. STEFANOV, A. PEER, M. BUSS.*Role determination in human-human interaction*, in "3rd Joint EuroHaptics Conf. and World Haptics", 2009, p. 51-56.

[57] R. S. SUTTON, A. G. BARTO.*Introduction to Reinforcement Learning*, MIT Press, 1998.

[58] A. TAPUS, M. MATARIĆ, B. SCASSELLATI.*The grand challenges in Socially Assistive Robotics*, in "IEEE Robotics and Automation Magazine - Special Issue on Grand challenges in Robotics", 2007, vol. 14, n° 1, p. 1-7.

[59] V. VASSILIADES, K. CHATZILYGEROUDIS, J.-B. MOURET.*Scaling Up MAP-Elites Using Centroidal Voronoi Tessellations*, in "arXiv:1610.05729", 2016.

[60] D. WILSON, C. ATKESON.*Simultaneous Tracking and Activity Recognition (STAR) Using Many Anonymous, Binary Sensors*, in "Pervasive Computing", H.-W. GELLERSEN, R. WANT, A. SCHMIDT (editors), Lecture Notes in Computer Science, Springer Berlin Heidelberg, 2005, vol. 3468, p. 62-79, http://dx.doi.org/10.1007/11428572_5.

[61] G. WOLBRING, S. YUMAKULOV.*Social Robots: Views of Staff of a Disability Service Organization*, in "International Journal of Social Robotics", 2014, vol. 6, n^{o} 3, p. 457-468.

Project-Team MADYNES

Management of dynamic networks and services

IN COLLABORATION WITH: Laboratoire lorrain de recherche en informatique et ses applications (LORIA)

IN PARTNERSHIP WITH:
CNRS

Université de Lorraine

RESEARCH CENTER
Nancy - Grand Est

THEME
Networks and Telecommunications

Table of contents

Project-Team MADYNES

Creation of the Project-Team: 2004 February 01, updated into Team: 2017 January 19

Keywords:

Computer Science and Digital Science:

1.1.4. - High performance computing
1.1.6. - Cloud
1.1.7. - Peer to peer
1.2. - Networks
1.3. - Distributed Systems
1.5. - Complex systems
4.1. - Threat analysis
4.9. - Security supervision
6.1.2. - Stochastic Modeling (SPDE, SDE)
6.1.3. - Discrete Modeling (multi-agent, people centered)
6.1.5. - Multiphysics modeling
6.2.6. - Optimization

Other Research Topics and Application Domains:

2.5.3. - Assistance for elderly
4.5. - Energy consumption
5.1. - Factory of the future
6.3.2. - Network protocols
6.3.3. - Network Management
6.4. - Internet of things
6.5. - Information systems
6.6. - Embedded systems
8.1. - Smart building/home
8.5. - Smart society
9.5.10. - Digital humanities
9.6. - Reproducibility

1. Members

Research Scientists

Jérôme François [Inria, Researcher]
Vassili Rivron [Inria, Researcher]

Faculty Members

Isabelle Chrisment [Team leader, Univ. Lorraine, Professor, HDR]
Laurent Andrey [Univ. Lorraine, Associate Professor]
Rémi Badonnel [Univ. Lorraine, Associate Professor]
Thibault Cholez [Univ. Lorraine, Associate Professor]
Laurent Ciarletta [Univ. Lorraine, Associate Professor]
Olivier Festor [Univ. Lorraine, Professor, HDR]

Abdelkader Lahmadi [Univ. Lorraine, Associate Professor]
Emmanuel Nataf [Univ. Lorraine, Associate Professor]
Lucas Nussbaum [Univ. Lorraine, Associate Professor]
Thomas Silverston [Univ. Lorraine, Associate Professor]
Yeqiong Song [Univ. Lorraine, Professor, HDR]

Technical Staff

Raphael Cherfan [Inria, until Aug 2016]
François Despaux [Univ. Lorraine]
Florent Didier [Inria, from Nov 2016]
Cédric Enclos [Univ. Lorraine, until Jun 2016]
Jérémie Gaidamour [Inria, until Sep 2016]
Adrien Guenard [Univ. Lorraine]
Sofiane Lagraa [Inria]
Clement Parisot [Inria]
Yannick Presse [Inria, granted by EDF]
Loic Rouch [Inria]
Cristian Camilo Ruiz Sanabria [Inria, until Oct 2016]
Benjamin Segault [Univ. Lorraine , until Oct 2016]
Alexandre Tan [Inria, granted by EDF]
Shuguo Zhuo [Inria]

PhD Students

Petro Aksonenko [Univ. Lorraine, from Jun 2016]
Jonathan Arnault [Inria, until Jun 2016]
Elian Aubry [Univ. Lorraine]
Pierre-Olivier Brissaud [Thales, granted by CIFRE]
Tomasz Buchert [Univ. Lorraine, until Jan 2016]
Paul Chaignon [Orange Labs, granted by CIFRE]
Maxime Compastie [Orange Labs, granted by CIFRE]
Giulia de Santis [Inria]
Florian Greff [Thales &Univ. Lorraine, granted by CIFRE]
Patrick Kamgueu [Univ. Lorraine, granted by Ministry of Foreign Affairs, since Jun 2012, in co-supervision with Université de Yaounde]
Daishi Kondo [CNRS]
Xavier Marchal [CNRS]
Anthea Mayzaud [Inria, until Oct 2016, granted by FP7 GA Flamingo project]
Thomas Paris [Univ. Lorraine]
Abdulqawi Saif [Xilopix, granted by CIFRE]
Nicolas Schnepf [Inria]
Wazen Shbair [Univ. Lorraine]
Salvatore Signorello [University of Luxembourg - Univ. Lorraine (co-advising)]
Evangelia Tsiontsiou [Univ. Lorraine]
Julien Vaubourg [Univ. Lorraine]
Kévin Roussel [Inria, until Sep 2016]

Post-Doctoral Fellows

Benoit Henry [Univ. Lorraine, until Nov 2016]
Mohamed Tlig [Univ. Lorraine, until Jun 2016]
Zhixiang Liu [Univ. Lorraine, from Dec 2016]
Lei Mo [Univ. Lorraine, until Sep 2016]

Visiting Scientist

Hong Zhou [Univ. Lorraine, from Sep 2016 until Oct 2016]

Administrative Assistants

Isabelle Herlich [Inria]
Delphine Hubert [Univ. Lorraine]
Martine Kuhlmann [CNRS]

Others

Paul Andrey [Univ. Lorraine, Internship ENSAE, from Jul 2016 until Aug 2016]
Nicolas Bedrine [Inria, Internship TELECOM Nancy, from Jun 2016 until Jul 2016]
Sébastien Coorevits [Inria, Internship TELECOM Nancy, from Jun 2016 until Jul 2016]
Marc Coudriau [Inria, Internship ENS Paris, from Jun 2016 until Aug 2016]
Yassine Elmrabet [Univ. Lorraine, Internship, from Mar 2016 until Jul 2016]
Mohamed Ezzeddine [Inria, Internship TELECOM Nancy, from Jun 2016 until Aug 2016]
Arthur Garnier [Inria, élève ingénieur en apprentissage, TELECOM Nancy]
Adrien Pheulpin [Inria, Internship TELECOM Nancy, from Jun 2016 until Aug 2016]
Antoine Richard [Univ. Lorraine, Internship from Sept 2016 until Dec 2016]
Quentin Rouy [Univ. Lorraine, Internship TELECOM Nancy, from Jun 2016 until Jul 2016]
Valentin Stern [Univ. Lorraine, Internship TELECOM Nancy, until Jul 2016]
Yoann Switala [Inria, Internship TELECOM Nancy, from Jun 2016 until Jul 2016]

2. Overall Objectives

2.1. Overall Objectives

The goal of the MADYNES research group is to design, to validate and to deploy novel management and security paradigms together with supporting software architectures and solutions that are able to cope with the growing dynamicity and the scalability issues induced by the ubiquitous Internet.

The project develops applied research activities in the following areas:

- **Autonomous Management**:
  - the design of models and methods enabling *self-organization and self-management* of networked entities and services,
  - the evaluation of management architectures based on *peer-to-peer and overlay principles*,
  - the investigation of novel approaches to the representation of *management information*,
  - the modeling and *performance evaluation* of dynamic networks.
- **Functional Areas** instantiate autonomous management functions:
  - the *security plane* where we focus on building closed-loop approaches to protect networking assets,
  - the *service configuration* where we aim at providing solutions covering the delivery chain from device discovery to QOS-aware delivery in dynamic networks,
  - *monitoring* where we aim at building solutions to characterize and detect unwanted service behavior.

The next generation Internet is the main application field of our research. Its architecture and the services that it is planned to support offer all dynamic and scalability features that we address in the complementary research directions of the project.

3. Research Program

3.1. Evolutionary needs in network and service management

The foundation of the MADYNES research activity is the ever increasing need for automated monitoring and control within networked environments. This need is mainly due to the increasing dependency of both people and goods towards communication infrastructures as well as the growing demand towards services of higher quality. Because of its strategic importance and crucial requirements for interoperability, the management models were constructed in the context of strong standardization activities by many different organizations over the last 15 years. This has led to the design of most of the paradigms used in today's deployed approaches. These paradigms are the Manager/Agent interaction model, the Information Model paradigm and its container, together with a naming infrastructure called the Management Information Base. In addition to this structure, five functional areas known under Fault, Configuration, Accounting, Performance and Security are associated to these standards.

While these models were well suited for the specific application domains for which they were designed (telecommunication networks or dedicated protocol stacks), they all show the same limits. Especially they are unable:

1. to deal with any form of dynamicity in the managed environment,
2. to master the complexity, the operating mode and the heterogeneity of the emerging services,
3. to scale to new networks and service environments.

These three limits are observed in all five functional areas of the management domain (fault, configuration, accounting, performance and security) and represent the major challenges when it comes to enable effective automated management and control of devices, networks and services in the next decade.

MADYNES addresses these challenges by focusing on the design of management models that rely on inherently dynamic and evolving environments. The project is centered around two core activities. These activities are, as mentioned in the previous section, the design of an autonomous management framework and its application to three of the standard functional areas namely security, configuration and performance.

4. Highlights of the Year

4.1. Highlights of the Year

4.1.1. Masdin associate team

Thanks to previously existing collaborations, a new associate team with SnT at University of Luxembourg has been created in 2016 with a focus on softwarization of networks.

5. New Software and Platforms

5.1. Distem

KEYWORDS: Large scale - Experimentation - Virtualization - Emulation
FUNCTIONAL DESCRIPTION

Distem is a distributed systems emulator. When doing research on Cloud, P2P, High Performance Computing or Grid systems, it can be used to transform an homogenenous cluster (composed of identical nodes) into an experimental platform where nodes have different performance, and are linked together through a complex network topology, making it the ideal tool to benchmark applications targetting such environments, or aiming at tolerating performance degradations or variations which are frequent in the Cloud or in other applications distributed at large scale (P2P for example).

- Participants: Luc Sarzyniec, Lucas Nussbaum and Tomasz Buchert
- Partners: CNRS - Grid'5000 - Inria - Loria - Université de Lorraine
- Contact: Lucas Nussbaum
- URL: http://distem.gforge.inria.fr

5.2. Grid'5000 testbed

FUNCTIONAL DESCRIPTION Grid'5000 is a scientific instrument designed to support experiment-driven research in all areas of computer science related to parallel, large-scale or distributed computing and networking. It gathers 10 sites, 25 clusters, 1200 nodes, for a total of 8000 cores. It provides its users with a fully reconfigurable environment (bare metal OS deployment with Kadeploy, network isolation with KaVLAN) and a strong focus on enabling high-quality, reproducible experiments.

- Participants: Luc Sarzyniec, Jérémie Gaidamour, Arthur Garnier, Clement Parisot, Emmanuel Jeanvoine, Lucas Nussbaum and Emile Morel
- Contact: Lucas Nussbaum
- URL: https://www.grid5000.fr/

5.3. Kadeploy

KEYWORD: Operating system provisioning
FUNCTIONAL DESCRIPTION

Kadeploy is a scalable, efficient and reliable deployment (provisioning) system for clusters and grids. It provides a set of tools for cloning, configuring (post installation) and managing cluster nodes. It can deploy a 300-nodes cluster in a few minutes, without intervention from the system administrator. It plays a key role on the Grid'5000 testbed, where it allows users to reconfigure the software environment on the nodes, and is also used on a dozen of production clusters both inside and outside Inria.

- Participants: Emmanuel Jeanvoine, Lucas Nussbaum and Luc Sarzyniec
- Partners: CNRS - Grid'5000 - Inria - Loria - Université de Lorraine
- Contact: Lucas Nussbaum
- URL: http://kadeploy3.gforge.inria.fr

5.4. MECSYCO-RE-C++

Multi-agent Environment for Complex SYstems COsimulation. Cœur C++
KEYWORDS: Modeling - Simulation - Simulator - Multi-model - Multi-agent - Agent - Artefact
FUNCTIONAL DESCRIPTION

MECSYCO is a project aiming at the modeling and simulation of complex systems. It provides concepts and tools to describe and then simulate a system as a set of heterogeneous models (namely a multi-model). MECSYCO-RE-C++ is the C++ implementation of the central part (core) of MECSYCO. It can be complimente by mecsyco-com (a communication package for distributed exécution) and mecsyco-visu (a set of tools for vizualizing simulations).

- Participants: Vincent Chevrier, Laurent Ciarletta, Benjamin Camus, Julien Vaubourg, Yannick Presse, Victorien Elvinger, Benjamin Segault and Nicolas Kirchner
- Partners: Inria - Université de Lorraine
- Contact: Vincent Chevrier

5.5. MECSYCO-RE-java

Multi-agent Environment for Complex SYstems COsimulation. Coeur java

KEYWORDS: Modeling - Simulation - Simulator - Multi-model - Co-simulation - Multi-agent - Agent - Artefact

FUNCTIONAL DESCRIPTION

MECSYCO is a project aiming at the modeling and simulation of complex systems. It provides concepts and tools to describe and then simulate a system as a set of heterogeneous models (namely a multi-model). MECSYCO-RE-java is the Java implementation of the central part (core) of MECSYCO. It can be complimente by mecsyco-com (a communication package for distributed exécution) and mecsyco-visu (a set of tools for vizualizing simulations).

- Participants: Christine Bourjot, Vincent Chevrier, Laurent Ciarletta, Benjamin Camus, Julien Vaubourg, Yannick Presse, Victorien Elvinger and Julien Siebert
- Partners: Inria - Université de Lorraine
- Contact: Vincent Chevrier
- URL: http://www.mecsyco.com

5.6. NDNperf

KEYWORDS: Performance measure - Named-Data Networking

FUNCTIONAL DESCRIPTION

We designed NDNperf, an open source tool for NDN server-side performance evaluation and sizing purposes, in order to have an idea of the throughput a server can achieve when it has to generate and transmit NDN Data packets. It is very similar to iPerf and also needs a client and a server to perform the measurements while minimizing the number of instructions between Interest reception and Data emission. It has the following features: - Periodic report of performances: end-to-end throughput, latency, processing time, - Fresh NDN Data generation or NDN Data delivery from caches, - Multi-threaded (one main thread for event lookup and N threads for NDN Data generation), - Able to use all available signatures implemented in the NDN library, choose the size of the key, and the transmission size of Data packets.

- Contact: Thibault Cholez
- URL: http://madynes.loria.fr/software/

5.7. Ruby-cute

KEYWORDS: Experimentation - HPC - Cloud

FUNCTIONAL DESCRIPTION

Ruby-Cute is a set of Commonly Used Tools for Experiments, or Critically Useful Tools for Experiments, depending on who you ask. It is a library aggregating various Ruby snippets useful in the context of (but not limited to) development of experiment software on distributed systems testbeds such as Grid'5000.

- Contact: Lucas Nussbaum
- URL: http://ruby-cute.github.io/

6. New Results

6.1. Monitoring

6.1.1. Quality of Experience Monitoring

Participants: Isabelle Chrisment [contact], Thibault Cholez, Vassili Rivron.

We have pursued our work on smartphone usage monitoring. In [26], we presented an exploratory smartphone usage study with logs collected from users in the wild, combined with the sociodemographic, technological and cultural information provided by them. We have shown that application usage among users is highly diverse. However when the applications are grouped as services, interesting relations appear between user profiles and types of services used. We found significant correlations between service usage and socio-demographic profile. We have proposed several possible use cases of how sociological information can be used to renew the official statistics, to recommend suitable applications to potential users.

6.1.2. Active Monitoring

Participants: Abdelkader Lahmadi [contact], Jérôme François, Frédéric Beck [LHS], Loic Rouch [LHS].

Following preliminary work in 2015, we pursued our assessment of industrial system exposition in the Internet. Industrial systems are composed of multiple components whose security has not been addressed for a while. Even if recent propositions target to improve it, they are still often exposed to vulnerabilities, since their components are hard to update or replace. In parallel, they tend to be more and more exposed in the public Internet for convenience. Although awareness of such a problem has been raised, there is no precise evaluation of such a risk. We thus defined a methodology to measure the exposure of industrial systems through Internet. In particular, a carefully designed scanning approach and software with a low footprint, named WiScan, consists in optimizing the distance between consecutively scanned IP addresses but being fast to compute. It has been applied on the entire IPv4 address space, by targeting specific SCADA ports. This work is reported in [20].

During the year 2016, we are also working with the regional PME TracIP http://www.tracip.fr on the development of attack assessment and forensics platform dedicated to industrial control system. The platform involves multiple PLC from different manufactures and real devices of factory automation systems.

6.1.3. SDN enhanced monitoring

Participants: Jérôme François [contact], Lautaro Dolberg [University of Luxembourg].

Software-Defined Networking (SDN) provides a highly flexible flow management platform through a logically centralized controller that exposes network capabilities to the applications. However, most applications do not natively use SDN. An external entity is thus responsible for defining the corresponding flow management policies. This is mainly the role of the network administrator, which also prefers to keep the control of its network rather than fully let the control to users or applications.

Usually network operators prefer to control the flow management policies, rather than granting full control to the applications. Although IP addresses and port numbers can suffice to identify users and applications in ISP networks and determine the policies applicable to their flows, such an assumption does not hold strongly in cloud environments. IP addresses are allocated dynamically to the users, while port numbers can be freely chosen by users or cloud-based applications. These applications, like computing or storage frameworks, use diverse port numbers which amplifies this phenomenon. We have proposed higher-level abstractions for defining user- and application-specific policies. In this scope, our framework transparently maps application-level policies (involving application and user names) to OpenFlow rules (IP addresses, protocols and port numbers), which alleviates the necessity for the control applications (those interacting with the Northbound interface of the controller) to keep track of the network characteristics (like location) of users and applications themselves. To achieve this end, application-level information is retrieved in real-time through local remote system agents, which can be easily deployed in a cloud platform where both network and computational infrastructure are hosted by the same entity.

Thus our work enables the association of flows with applications and users. It led to a publication [19].

6.1.4. Service-level Monitoring of HTTPS traffic

Participants: Thibault Cholez [contact], Shbair Wazen, Jérôme François, Isabelle Chrisment.

We previously investigated the latest technique for HTTPS traffic filtering that is based on the Server Name Indication (SNI) field of TLS and which has been recently implemented in many firewall solutions. We showed that SNI has two weaknesses, regarding (1) backward compatibility and (2) multiple services using a single certificate. On the other side, HTTPS proxy suffers from privacy issues by decrypting users' sensitive traffic. This led us to the development of new reliable methods to investigate the increasing number of HTTPS traffic with a proper level of identification (service-level) that allows the management of the traffic while other methods are either too broad (protocol-lvl identification) or too precise (page-level identification).

We proposed to improve HTTPS traffic monitoring based on SNI. Our investigation shows that 92% of the HTTPS websites surveyed can be accessed with fake-SNI. Our approach verifies the coherence between the real destination server and the claimed value of SNI by relying on a trusted DNS service. Experimental results show the ability to overcome the shortage of SNI-based monitoring by detecting forged SNI values while having a very small false positive rate (1.7%). The overhead of our solution only adds negligible delays to access HTTPS websites. The proposed method opens the door to improve global HTTPS monitoring and firewall systems and was published in the IEEE STAM workshop [31].

We proposed an alternative technique to investigate HTTPS traffic which aims to be robust, privacy-preserving and practical with a service-level identification of HTTPS connections, i.e. to name the services, without relying on specific header fields that can be easily altered. We have defined dedicated features for HTTPS traffic that are used as input for a multi-level identification framework based on machine learning algorithms processing full TLS sessions. Our evaluation based on real traffic shows that we can identify encrypted web services with a high accuracy. This work was published in IFIP/IEEE NOMS [30] and is now extended in the frame of the CNRS PEPS NEFAE project to address the challenge of real-time monitoring of HTTPS. We extract statistical features on TLS handshake packets and progressively on application data packets, so that we can identify HTTPS services very early in the session. Extensive experiments performed over a significant and open dataset show that our method offers a good accuracy and a prototype implementation confirms that the real-time requirement of monitoring HTTPS services is satisfied.

6.1.5. Sensor networks monitoring

Participants: Rémi Badonnel, Isabelle Chrisment, Olivier Festor, Abdelkader Lahmadi [contact], Anthea Mayzaud.

This year, we have pursued our work on IoT security monitoring, based on our distributed architecture specified in [24]. This one exploits the multi-instance mechanisms of the RPL protocol, to build a monitoring plane using high-order nodes, in the context of Advanced Metering Infrastructures (AMI). It permits to preserve more constrained node resources, by passively monitoring the network. We have shown in [23] its benefits for detecting version number attacks. A DODAG versioning system is incorporated into the RPL protocol, in order to ensure an optimized topology. However, an attacker can exploit this mechanism to damage the network and reduce its lifetime. We have therefore proposed a detection strategy with a set of algorithms capable of identifying malicious nodes performing such attacks. We have evaluated our solution through experiments and have analyzed the performance according to defined metrics. We have shown that false positive rates can be reduced by a strategic monitoring node placement. In particular, we have addressed scalability considerations, as an optimization problem which can be easily adapted to different topologies. By resolving this problem, we were able to quantify the number of monitoring nodes required to ensure an acceptable false positive rate for different topologies.

Our taxonomy on security attacks in these networks has also been published in [2]. The RPL protocol is exposed to a large variety of attacks, whose consequences can be quite significant in terms of network performance and resources. The attacks against resources reduce network lifetime through the generation of fake control messages or the building of loops. The attacks against the topology make the network converge to a sub-optimal configuration or isolated nodes. Attacks against network traffic let a malicious node capture and analyse large part of the traffic. This classification serves as a support to prioritize attacks depending on the damages they may cause to the network, and can be exploited for risk management purposes in order to select counter-measures.

6.2. Security

6.2.1. Security analytics

Participants: Jérôme François [contact], Abdelkader Lahmadi, Giulia de Santis, Marc Coudriau, Olivier Festor.

During 2016, active collaboration with the High Security Lab in Nancy continues especially in the context of the FUI HuMa project. First we developed a method to automatically analyze darknet data. A darknet or telescope is a whole subnetwork, which is announced over Internet such that packets sent to the IP addresses are properly routed over but not replied to. In our case, the darknet is a /20 network meaning that we monitor 2^{12} addresses. The main challenge we faced was to cope with the volume of data in order to extract intertwined phenomena characterized by groups of packets. We proposed a clustering and visualisation method derived from the Mapper algorithm that has been developed in the field of Topological Data Analysis (TDA). The developed method and its associated tool are able to analyze a large number of IP packets in order to make malicious activity patterns easily observable by security analysts. The results show that our method is able to exhibit observable patterns which have been missed by Suricata, a widely used State-of-the-Art IDS https://hal.inria.fr/hal-01403950/document.

Second scannings have been particularly studied as they represent the first phase of recognition in advanced persistent threats. While it is known that every exposed systems is always being actively scanned from multiple sources, it is still challenging to fingerprint them, in particular to identify what are the distributed sources of a single synchronized scan and what is the tool used to generate it. As a first step, we proposed a methodology based on Hidden Markov Models (HMMs) to model scanning activities monitored by a darknet [18]. The HMMs of scanning activities are built on the basis of the number of scanned IP addresses within a time window and fitted using mixtures of Poisson distributions.

We are also still maintaining an IRTF draft [50] to promote a standardization effort towards the extension of IP Flow-based monitoring with geographic information. Associating Flow information with their measurement points geographic locations will enable security applications to detect anomalous activities. In the case of mobile devices, the characterization of communication patterns using only time and volume is not enough to detect unusual location-related communication patterns. The draft went through an IRSG review and a feedback is still required from the OPSWAG IETF working group.

6.2.2. DDoS Signaling

Participants: Jérôme François [contact], Abdelkader Lahmadi, Giovane Moura [SIDN Labs, Netherland], Marco Davids [SIDN Labs, Netherlands].

A distributed denial-of-service (DDoS) attack aims at rendering machines or network resources unavailable. These attacks have grown in frequency, intensity and target diversity. In the context of Flamingo, Madynes contributed to the definition of an opportunistic signaling protocol in cooperation with SIDN Labs in Netherlands. The goal is to provide an efficient mechanism where nodes in an IPv6 network facing a DDoS attack can deliver a DOTS (DDoS Open Threat Signaling) signal message sent by a DOTS client to the DOTS server. The specified mechanism does not generate transport packets to carry the DOTS signal message but it only relies on existing IPv6 packets in the network to include within them a hop-by-hop extension header which contains an encoded DOTS signal message.

This work is done under the umbrella of our standardization activities especially within the IETF DOTS working group [45] and was presented during IETF 96 in Berlin.

6.2.3. NDN Security

Participants: Thibault Cholez [contact], Xavier Marchal, Olivier Festor.

Named-Data Networking (NDN) is one of the most advanced ICN architecture but the security of NDN or NFD (NDN Forwarding Deamin) is still in the early stages and not ready for real deployment. In the context of the ANR Doctor project, we investigate NDN security in order to unveil issues and propose remediations.

First, we discovered a new vulnerability of NDN which is easy to exploit and can lead to very serious attacks, badly affecting the network. This vulnerability is due to an absence of control at the precise moment when NFD receives an incoming Data. In fact, NFD only checks two points: if the Data belongs to the localhost scope, or if it matches an existing PIT entry, but not if the Data comes from a valid Face. This is a critical shortage because it allows malicious users to directly send Data to perform attacks like DoS and cache poisoning without having to register a prefix in the router's FIB beforehand to receive legitimate Interests. After these checks, NFD continues to process the Data packet. The NDN protocol makes the hypothesis that a node cannot send a Data packet without having previously received the corresponding Interest (receiver driven communication). However, NFD should consider malicious nodes that decide to not follow the standard way to proceed with NDN communications and send Data unexpectedly. We further described two serious attack scenarios exploiting this vulnerability based on the fact that malicious nodes can send unexpected Data that can consume legitimate PIT entries. We also propose two ways to prevent it with minor modifications in NFD. This work was published and demonstrated at the ACM-ICN conference [46].

Second, we addressed the Content Poisoning Attack (CPA), known to be one of the major threats in NDN. So far, existing works in that area have fallen into the pit of coupling a biased and partial phenomenon analysis with a proposed solution, hence lacking a comprehensive understanding of the attack's feasibility and impact in a real network. In the context of the ANR Doctor Project, and in collaboration with UTT, we demonstrated through an experimental measurement campaign that CPA can easily and widely affect NDN. We proposed three realistic attack scenarios relying on both protocol design and implementation weaknesses and presented their implementation and evaluation in a testbed based on the latest NFD version. We analyzed their impact on the different ICN nodes composing a realistic topology (clients, access and core routers, content provider) in order to fully characterize the CPA. This work has been accepted and will be published in IFIP/IEEE IM 2017 conference.

6.2.4. Configuration security automation

Participants: Rémi Badonnel [contact], Abdelkader Lahmadi, Olivier Festor, Nicolas Schnepf, Maxime Compastie.

We have pursued during year 2016 our efforts on the orchestration of security functions in the context of mobile smart environments, with a joint work with Stephan Merz of the VeriDis project-team at Inria Nancy. In particular, Nicolas Schnepf studied during his Master thesis formal techniques for the automatic verification of chains of security functions in a setting of software-defined networks (SDN). Concretely, he defined an extension of the Pyretic language [51] which takes into account the data plane of SDN controllers and implemented a translation of that extension to the input languages of the nuXmv model checker and of SMT solvers. The approach and its scalability were validated over crafted security chains, and a conference paper describing the results is going to be submitted shortly. Nicolas Schnepf started a PhD thesis on the same topic in October 2016 with joint supervision by members of the Madynes and VeriDis Inria project-teams.

In addition, we have analyzed and evaluated the usage of OpenFlow messages for security applications [29], jointly with Bundeswehr University of Munich. The purpose was to quantify the performances of security solutions that are built on top of software-defined networking infrastructures. We have considered overloading attacks and information gathering attacks, that are quite common in these environments, and have detailed regular and sdn-based mitigation mechanisms that have been designed for tackling them. We have then analyzed for each category the dependencies of these mechanisms to the OpenFlow protocol commonly supporting the communications between sdn controllers and switches. These dependencies have been identified through the mapping of OpenFlow messages to security functionalities in that context. Based on this analysis, we performed series of experiments on two different testbeds for comparing and evaluating the accuracy and reliability that can be expected with respect to these messages.

We have also investigated in [16] a software- defined security framework, for supporting the enforcement of security policies in distributed cloud environments. These latter require security mechanisms able to address their multi-tenancy and multi-cloud properties. This framework relies on the autonomic paradigm to dynamically configure and adjust these mechanisms to distributed cloud constraints, and exploit the software-defined logic to express and propagate security policies to the considered cloud resources. It exploits a security orchestrator, policy decision points (PDP) and policy enforcement point (PEP) interacting according to a dedicated set of protocols, and will take advantage of facilities offered by unikernel and micro-services techniques to reduce the security exposure of cloud resources. The proposed framework has been evaluated so far through a set of validation scenarios corresponding to a realistic use cases including cloud resource allocation/deallocation, cloud resource state change, and dynamic access control.

6.3. Experimentation, Emulation, Reproducible Research

This section covers our work on experimentation on testbeds (mainly Grid'5000), on emulation (mainly on Distem), and on Reproducible Research.

6.3.1. Grid'5000 design and evolutions

Participants: Jérémie Gaidamour, Arthur Garnier, Lucas Nussbaum [contact], Clément Parisot, Florent Didier.

The team was again heavily involved in the evolutions and the governance of the Grid'5000 testbed.

First, we finished the installation and setup of several new clusters in the Nancy site, which brought several new local users, from various teams, to the testbed.

In the context of ADT LAPLACE, Jérémie Gaidamour added support for the control of CPU parameters such as Hyperthreading, Turboboost, P-states and C-states. It is expected that this work will enable interesting usages in the areas of HPC runtimes and energy-aware computing.

Finally, in the context of his roles in the *bureau*, *comité d'architectes* and *comité des responsables de sites* of Grid'5000, Lucas Nussbaum managed the purchase of the new clusters at Nancy mentioned above, and gave several presentations about the testbed, at the *Grid'5000 School* [5] [38], at a GENI-FIRE collaboration workshop [9], [8], [6], [7].

6.3.2. Emulation with Distem

Participants: Emmanuel Jeanvoine, Lucas Nussbaum [contact], Cristian Ruiz.

Several improvements have been made around Distem, mostly in the context of ADT COSETTE.

A paper demonstrating the use of Distem to evaluate fault tolerance and load balancing strategies implemented in Charm++ was accepted at CCGrid'2016 [28].

We continued our work on using Distem to experiment on NDN infrastructures. We obtained promising results, especially in terms of scale. This work is still pending publication.

Finally, we also evaluated the porting of Distem to other testbeds (ChameleonCloud and CloudLab), which was interesting for Distem specifically, but also to understand differences between those testbeds [43].

6.3.3. Management of experiments

Participants: Tomasz Buchert, Emmanuel Jeanvoine, Lucas Nussbaum [contact], Cristian Ruiz.

We continued work on Ruby-Cute, a library that aggregates various useful functionality in the context of such tools. Several releases were made in 2016. We hope that it will be useful as a basis for future tools, and ease testing of new ideas in that field. The library is available on http://ruby-cute.github.io/.

Tomasz Buchert defended his PhD thesis, entitled *Managing large-scale, distributed systems research experiments with control-flows*, in January 2016 [1].

6.3.4. Experimentation methodologies on Big Data

Participants: Abdulqawi Saif, Lucas Nussbaum [contact], Ye-Qiong Song [contact].

Abdulqawi Saif started his PhD on experimentation methodologies for Big Data at the end of 2015. His first work [35] is a multi-criteria analysis of NFS performance using statistical Design of Experiments techniques.

6.4. Routing

6.4.1. Probabilistic Energy-Aware Routing for Wireless Sensor Networks

Participants: Evangelia Tsiontsiou, Bernardetta Addis, Alberto Ceselli [Universita degli Studi di Milano], Ye-Qiong Song [contact].

Healthcare applications are considered as promising fields for Wireless Sensor Networks (WSNs) and globally IoT. Thanks to WSNs, patients can be monitored in hospitals or smart home environments, providing health improvement, or emergency care. Network lifetime is still the key issue when we deploy wireless sensor networks and IoT solutions in real-world applications. Current WSN research trends include duty-cycling at MAC layer and energy efficient routing at network layer, among others. We proposed an Optimal Probabilistic Energy-Aware Routing Protocol (OPEAR) for duty-cycled WSNs which aims at maximizing the network lifetime by keeping low energy consumption and balancing network traffic between nodes. Our experimental campaign reveals that our OPEAR protocol outperforms the popular Energy Aware Routing Protocol (EAR) from the literature, proving to be more effective in extending the network lifetime [33]. It is part of Lorraine AME Satelor project granted by Lorraine Region.

6.4.2. NDN router with P4

Participants: Salvatore Signorello [University of Luxembourg], Olivier Festor [contact], Radu State [University of Luxembourg], Jérôme François.

Although content-awareness at the network level is becoming more and more needed, Information-Centric Networking (ICN)-based solutions struggle to emerge. Research on ICN has already produced insightful outputs, nevertheless architecture-tied designs of ICN devices cannot be easily deployed and tested in operational networks; further those designs are hard to share. In the meantime, the vision of Software-Defined Networking has grown and taken new shapes. Network players desire to change devices' behavior often and drastically, even though performances are still crucial to operate at line-speed. This has been leading to a rethink of network devices designs with the aim to offer full-programmability through high-level programming languages for packet processors, like P4. It is a programming language to describe the forwarding plane of network devices. The language abstracts how packets are processed by different devices in target- independent programs. Then, compilers map those programs to different forwarding devices with as final goal a single specification which can be automatically mapped to hardware or software implementations. Although high-level protocols like ICN with advanced parsing mechanisms are usually handled by software switch with standard programming capacity, P4 would allow more efficient implementation on specific platform. Our preliminary implementation strives to implement many features of the NDN routing by using native P4 language constructs only [32].

6.4.3. NDN/HTTP cohabitation

Participants: Thibault Cholez [contact], Xavier Marchal, Olivier Festor.

Network operators are reluctant to deploy globally Named Data Networking (NDN) because of the huge investment costs required and the uncertainty about the security and the manageability of such disruptive network protocols when deployed in production, while the return of investment is also uncertain. Meanwhile, Network Functions Virtualization (NFV) greatly facilitates the deployment of novel networking architectures by reducing the costs thanks to the usage of commodity hardware in place of dedicated equipments. Consequently, leveraging NFV to ease the deployment of NDN infrastructures appears as a strong mean to incite network operators to adopt this technology. In this context, the challenge we address in the ANR DOCTOR project is to fulfil the requirements needed to move NDN from a solution restricted to labs or tesbeds to a fully operational one by developing NDN-specific Virtual Network Functions (VNF).

In this effort, one of the main first questions which arise is about the integration of NDN into the existing Internet, and particularly the collocation of NDN with IP and HTTP. We think that a good way to deploy NDN consists in creating virtualized NDN island that can be crossed by specific content-related traffic, such as HTTP, and thus benefit from NDN properties (caching, aggregation, etc.). We proposed and developed an early version of a fully-capable NDN/HTTP gateway that can seamlessly connect a NDN network to the rest of the World Wide Web. This work was published and demonstrated at the ACM-ICN conference [47].

6.5. Multi-modeling and co-simulation

Participants: Laurent Ciarletta [contact], Olivier Festor, Ye-Qiong Song, Yannick Presse, Julien Vaubourg, Alexandre Tan, Benjamin Segault, Thomas Paris.

Vincent Chevrier (former Maia team, Dep 5, LORIA) is a collaborator and the correspondant for the MS4SG/MECSYCO project, Benjamin Camus, and Christine Bourjot (former MAIA team, Dep 5, LORIA) are collaborators for AA4MM/MECSYCO. Julien Vaubourg and Thomas Paris's PhDs are under the co-direction of V. Chevrier and L. Ciarletta.

In Pervasive or Ubiquitous Computing, a growing number of communicating/computing devices are collaborating to provide users with enhanced and ubiquitous services in a seamless way.

These systems, embedded in the fabric of our daily lives, are complex: numerous interconnected and heterogeneous entities are exhibiting a global behavior impossible to forecast by merely observing individual properties. Firstly, users physical interactions and behaviors have to be considered. They are influenced and influence the environment. Secondly, the potential multiplicity and heterogeneity of devices, services, communication protocols, and the constant mobility and reorganization also need to be addressed. Our research on this field is going towards both closing the loop between humans and systems, physical and computing systems, and taming the complexity, using multi-modeling (to combine the best of each domain specific model) and co-simulation (to design, develop and evaluate) as part of a global conceptual and practical toolbox.

We proposed the AA4MM meta-model [52] that solves the core challenges of multimodeling and simulation coupling in an homogeneous perspective. In AA4MM, we chose a multi-agent point of view: a multi-model is a society of models; each model corresponds to an agent and coupling relationships correspond to interaction between agents. In the MECSYCO-NG (formerly MS4SG, Multi Simulation for Smart Grids) projet which involves some members of the former MAIA team, Madynes and EDF R&D on smart-grid simulation, we developed a proof of concepts for a smart-appartment case that serves as a basis for building up use cases, and we have worked on some specific cases provided by our industrial partner.

In 2016 we worked on the following research topics:

- Assessment and evaluation of complex systems.
- Cyber Physical Systems.

  We have pursued the design and implementation of the Aetournos platform at Loria. The collective movements of a flock of flying communicating robots / UAVs, evolving in potentially perturbed environment constitute a good example of a Cyber Physical System.

  We have maintained thanks to the ADT UASS a set of tools: multi-simulation behavior / network / physics and generic software development using ROS (Robot Operating System). The UAVs carry a set of sensors for location awareness, their own computing capabilities and several wireless networks.
- MS4SG / MECSYCO-NG opportunity to link simulations tools with a strong focus on FMI (Functional Mockup Interface) and network simulators (NS3/Omnet++) thanks to our MECSYCO (formerly AA4MM) framework. We have so far successfully applied our solution to the simulation of smart apartment complex and to combine the electrical and networking part of a Smart Grid. The AA4MM software is now MECSYCO and has seen major improvements in 2016 thanks to the ressources provided by the MECSYCO-NG project in collaboration with EDF R&D (http://www.mecsyco.com).

Starting from domain specific and heterogenous models and simulators, the MECSYCO suite allows for multi *systems* integration at several levels: conceptual, formal and software. A couple of visualization tools have been developed as proof of concepts both at run-time and post-mortem.

We have developed software components and plugins that interconnects within MECSYCO heterogeneous simulators from different domains: FMU (working with the 1.0 and 2.0 FMI standard for CoSimulation) ou non-FMU such as NS3 or Omnet++.

Several EDF oriented advanced use cases have demonstrated multi-simulations.

In addition to technical reports [41], several publications have been accepted in 2016 on these subjects [25], [13] and [34].

6.6. Pervasive or Ubiquious Computing

Participants: Laurent Ciarletta [contact], Olivier Festor, Ye-Qiong Song, Emmanuel Nataf, Thomas Paris, Benjamin Segault, Antoine Richard, Petro Aksonenko.

P. Aksonenko PhD is under the co-direction of L. Ciarletta and Patrick Henaff from Loria Dep 5. Thomas Gurriet, now PhD student at Georgia Tech under the supervision of Prs Eric Feron and Aaron Ames is contributing to the topic of CPS safety.

In Pervasive or Ubiquitous Computing, a growing number of communicating/computing devices are collaborating to provide users with enhanced and ubiquitous services in a seamless way.

These systems, increasingly numerous and heterogeneous, are embedded in the fabric of our daily lives. Our initial subject of interest is to study them with regards to their complexity: Those numerous interconnected and heterogeneous entities are exhibiting a global behavior impossible to forecast by merely observing individual properties.

Firstly, users physical interactions and behaviors have to be considered. They are influenced and influence their surroundings and the environment. Secondly, the potential multiplicity and heterogeneity of devices, services, communication protocols, and the constant mobility and reorganization also need to be addressed. Thirdly we are aking into account their dynamcity, with regards to their mobility and evolving context.

Our research on this field is going towards both closing the loop between humans and systems, physical and computing systems, and taming the complexity, using multi-modeling (to combine the best of each domain specific model) and co-simulation (to design, develop and evaluate) as part of a global conceptual and practical toolbox.

In 2016 we mainly worked on the Cyber Physical Systems.

We maintained the Aetournos platform at Loria in collaboration with 6PO and the support of ADT UASS. We are studying the collective movements of a flock of flying communicating robots / UAVs, evolving in potentially perturbed environment constitute a good example of a Cyber Physical System.

The effort put in the UAVs gathers academic and research ressources from the Aetournos platform, the Inria ADT R2D2 and the 6PO project, while applied, industrial and more R&D projects have been pursued this year (Medical Express / Outback Joe Search and Rescue Challenge, Alerion, Hydradrone, and a CIFRE PhD with Thales for example) .

This also led to two new accepted projects:

- one Interreg "Grone", a generic project about drones in industrial and agricultural environments, started in October 2016
- and one FUI22 "CEOS", about insuring safety in UAVs at the system level that will start in 2017

  One of the emerging topic in this area is the safety of Mobile IoT / CPS with regards to their environment and users. This gave first results on how to design the internal communication system [21], the overal system [15], specific safety solutions [14] and a US Patent has been filled on a termination system led by Georgia Tech [Optimal Emergency Termination System for Unmanned Aerial Vehicles by Destructive Rotor Surface Reduction, Application No.: 62/378,923].
- Smart * (MECSYCO)

We have studied scientific problems around models and simulators composition. We have also looked into practical and implementation issues in the frame of our MECSYCO /AA4MM solutions. We have added to our Smart Grid scenarios a smart appartment complex use case.

- (Very Serious) Gaming: Starburst Gaming. During some exploratory work, we have seen the potential of these Pervasive Computing ressources in the (Very Serious) Gaming area.

6.7. Quality-of-Service

6.7.1. Self-adaptive MAC protocol for both QoS and energy efficiency

Participants: Kévin Roussel, Shuguo Zhuo, Olivier Zendra, Ye-Qiong Song [contact].

WSN research focus has progressively been moved from the energy issue to the QoS issue. Typical example is the MAC protocol design, which cares about not only low duty-cycle at light traffic, but also high throughput with self-adaptation to dynamic traffic bursts.

We have mainly contributed to enhancing the implementation of the high efficient traffic self-adaptive MAC protocols. As part of RIOT ADT project, we have improved and implemented a fully functional iQueue-MAC which provides not only the unique feature of high traffic self-adaptivity, but also the robustness by using two control channels (https://github.com/RIOT-OS/RIOT/pull/5618).

As part of LAR project, we were interested by using the Cooja/MSPSim network simulation framework for RIOT OS based platforms. We have showed that Cooja is not limited only to the simulation of the Contiki OS based systems and networks, but can also be extended to perform simulation experiments of other OS based platforms, especially that with RIOT OS. Moreover, when performing our own simulations with Cooja and MSPSim, we observed timing inconsistencies with identical experimentations made on actual hardware. Such inaccuracies clearly impair the use of the Cooja/MSPSim framework as a performance evaluation tool, at least for time-related performance parameters. The detailed results of our investigations on the inaccuracy problems, as well as the consequences of this issue, and possible ways to fix or avoid it are available in [27].

6.7.2. QoS and fault-tolerance in distributed real-time systems

Participants: Florian Greff, Laurent Ciarletta, Arnauld Samama [Thales TRT], Eric Dujardin [Thales TRT], Ye-Qiong Song [contact].

The QoS must be guaranteed when dealing with real-time distributed systems interconnected by a network. Not only task schedulability in processors, but also message schedulability in networks should be analyzed for validating the system design. Fault-tolerance is another critical issue that one must take into account. In collaboration with Thales TRT industrial partner as part of a CIFRE PhD work, we started a study on the real-time dependability of distributed multi-criticity systems interconnected by an embedded mesh network (RapidIO). For easing the QoS specification at the higher level, DDS middleware is used. We postulate that enhancing QoS for real-time applications entails the development of a cross-layer support of high-level requirements, thus requiring a deep knowledge of the underlying networks. This year, we proposed and implemented a new simulation/emulation/experimentation framework called ERICA, for designing such a feature. ERICA integrates both a network simulator (Ptolemy) and an actual hardware network to allow implementation and evaluation of different QoS-guaranteeing mechanisms. It also supports real-software-in-the-loop, i.e. running of real applications and middleware over these networks [21].

We have also dealt with mesh networking of embedded components. Our approach is to allow applications to make online real-time flow resource requests and consequently dynamically allot network resources according to these requirements. To this end, additional mechanisms must be provided in order to meet the real-time constraints while the platform remains as dynamic as possible. We gather these mechanisms into a Software-Defined Real-time Network (SDRN) paradigm. The online admission control and pathfinding algorithms have been developed allowing the controller to dynamically configure the real-time network nodes. We have evaluated several pathfinding algorithms.

6.7.3. Wireless sensor and actuator networks

Participants: Lei Mo, Adrian Guenard, Yifei Qi [Zhejiang University], Jiming Chen [Zhejiang University], Ye-Qiong Song [contact].

Wireless sensor and actuator networks provide a key technology for fully interacting within a CPS (Cyber-Physical System). However, the introduction of the mobile actuator nodes in a network rises some new challenging issues. In this context, we addressed two important issues: the multiple target tracking using both fixed and mobile sensors and the optimal scheduling of mobile wireless energy chargers (actuators) for fixed sensor nodes.

In the low-cost and large-scale deployment of mobile sensor nodes for target tracking, due to the constraints of limited sensing range, it is of great importance to design node coordination mechanism for reliable tracking so that at least the target can always be detected with a high probability, while the total network energy cost can be reduced for longer network lifetime. In [3], we dealt with this problem considering both the unreliable wireless channel and the network energy constraint. We transfer the original problem into a dynamic coverage problem and decompose it into two subproblems. By exploiting the online estimate of target location, we first decide the locations where the mobile nodes should move into so that the reliable tracking can be guaranteed. Then, we assign different mobile nodes to each location in order that the total energy cost in terms of moving distance can be minimized. Extensive simulations under various system settings have shown the effectiveness of our solution.

We also investigated the multiple mobile chargers coordination problem that is minimizing the energy expenditure of the mobile chargers while guaranteeing the perpetual operation of the wireless sensor network. We extended our previous result (published in IPCCC2015) by taking into account mobile charger's charging ability. We formulated this problem as a mixed-integer linear program (MILP), and proposed a novel decentralized method which is based on Benders decomposition. The convergence of proposed method is analyzed theoretically. Simulation results demonstrate the effectiveness and scalability of the proposed method.

6.7.4. NDN performance evaluation

Participants: Thibault Cholez [contact], Xavier Marchal, Olivier Festor.

NDN (Named Data Networking) is a promising protocol that can help to reduce congestion at Internet scale by putting content at the center of communications instead of hosts. NDN can also natively authenticate transmitted content with a mechanism similar to website certificates that allows clients to assess the original provider. But this security feature comes at a high cost, as it relies heavily on asymmetric cryptography which affects server performance when NDN Data are generated. This is particularly critical for many services dealing with real-time data (VOIP, live streaming, etc.), but current tools are not adapted for a realistic server-side performance evaluation of NDN traffic generation when digital signature is used. We propose a new tool, NDNperf, to perform this evaluation and show that creating NDN packets is a major bottleneck of application performances. On our testbed, 14 server cores only generate $\sim$400 Mbps of new NDN Data with default packet settings. We gave recommendation about the configuration of NDN (packet size, cryptographic function) and proposed practical improvements to the NDN library that all combined can vastly increase the performance of server-side NDN Data generation (x8,5). This work was published in the ACM-ICN conference [22].

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

- Xilopix (Epinal, France):
  - Pay-per-use contract for the use of Grid'5000
  - Support contract for their use of Grid'5000 (define experimental requirements and plans)

7.2. Bilateral Grants with Industry

- CIFRE, Thales TRT (Paris, France):
  - CIFRE PhD (Florian Greff, supervised by Ye-Qiong Song and Laurent Ciarletta)
  - Dynamic reconfiguration and graceful degradation of distributed real-time applications over mesh networks
- CIFRE, Orange Labs (Issy-Les-Moulineaux, France)
  - CIFRE PhD (Maxime Compastie, supervised by Olivier Festor and Rémi Badonnel)
  - Software-Defined Security for Distributed Cloud Infrastructures
- CIFRE, Orange Labs (Issy-Les-Moulineaux, France)
  - CIFRE PhD (Paul Chaignon, supervised by Olivier Festor and Jérôme François)
  - Monitoring of Software-Define Networks
- CIFRE, Xilopix (Epinal, France):
  - CIFRE PhD (Abdulqawi Saif, supervised by Ye-Qiong Song and Lucas Nussbaum)
  - Open Science for the scalability of a new generation search technology
- CIFRE, Thales (Elancourt, France)
  - CIFRE PhD (Pierre-Olivier Brissaud, supervised by Isabelle Chrisment and Jérôme François)
  - Anomaly detection in encrypted traffic

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. 6PO Research Region Lorraine and UL project

Participants: Emmanuel Nataf, Ye-Qiong Song, Laurent Ciarletta [contact].

Funded by Region Lorraine and Université de Lorraine since 2013. Adel Belkadi (CRAN & LORIA) is co-directed by L. Ciarletta and Didier Theilliol (CRAN correspondant).

6PO ("Systèmes Cyber-Physiques et Commande Coopérative Sûre de Fonctionnement pour une Flotte de Véhicules sans Pilote") is a joint research project between the Loria and CRAN laboratories. As a part of the Aetournos ecosystem, it also aims at researching solutions for safe formation flying of collaborative UAVs seen as part of a collection of Cyber Physical Systems mixing computer science and automation solutions.

It is reinforced by a PhD grant from this federation that started in october 2014 (*Conception de méthodes de diagnostic et de tolérance aux fautes des systèmes multi-agents: Application à une flotte de véhicules autonomes*, Adel Belkadi).

This led to common publications, notably on the subjects of the robust control of a fleet or flock of UAVs (with or without leader, using agents paradigms and particle swarm optimisation [12] and [36]).

The project provides common use cases and scientific challenges that serve as catalysts for collaboration between teams from different research topics :

- Cyber Physical Systems, Real Time, Quality of service, Performance and Energy in Wireless Sensors and Activator Networks
- Collaborative, communicating autonomous systems and Unmanned Vehicles
- Safety, Dependabilty, Reliability, Diagnosis, Fault-Tolerance

8.1.2. Hydradrone FEDER Région Lorraine project

Participants: Adrien Guenard, Zhixiang Liu, Laurent Ciarletta [contact].

Feder funding

The Madynes team has been working on the Hydradrone project since July 2014. It started as a collaborative R&D initiative funded by *Région Lorraine* and is now FEDER funded. This project started as a joint work between Madynes and PEMA (*Pedon Environnement et Milieux Aquatiques*), an SME/VSE (small and medium size Entreprise, PME/TPE). The consortium now includes Alerion another VSE, spinoff from Loria.

It consists in developing a new solution for the surveillance of aquatic environment, the Hydradrone:

- starting with an actual need for automated and remote operation of environmental sensing expressed by PEMA
- based on an hybrid UxV (Unmanned Air, Surface... Vehicle),
- some Cyber Physical bricks in coherence with the Alerion's concepts (ease of use, safety, autonomy)
- and an integration in the Information System of the company

PEMA, as an environmental company, is providing the use cases and terrain (and business) validation, while Alerion is working on the integration and engineering of the solution.

This second year has been dedicated to the development of the initial controllers for the Hydradrones (smal and large one), and the beginning of the integration of the environmental sensors.

8.1.3. Satelor AME Lorraine regional project

Participants: François Despaux, Lei Mo, Mohamed Tlig, Bernardetta Addis, Evangelia Tsiontsiou, Ye-Qiong Song [contact].

The Madynes team is involved in Satelor, a regional research and development project funded by the AME (Agence de Mobilisation Economique) of Lorraine (October 2013 – September 2017). The consortium includes academic (Univ. of Lorraine, Inria), medical (OHS) and industrial (Diatelic-Pharmagest (lead), ACS, Kapelse, Salendra, Neolinks) partners. It aims at developing innovative and easily deployable ambient assisted living solutions for their effective use in the tele-homecare systems. The Madynes team is mainly involved in the data collection system development based on wireless sensors networks and IoT technology. The first topic consists in defining the basic functions of the future SATEBOX – a gateway box for interconnecting in-home sensors to the medical datacenter, based on our previously developed MPIGate software. A beta-version prototype of the future Satebox gateway has been realased. It now includes Zigbee wireless sensors, EnOcean battery-free sensors and Bluetooth Low Energy sensors. It provides a low-cost and easily deployable solution for the daily activity monitoring. After its first real-world deployment at a OHS hospital room, a second prototype testbed has been prepared for a further test deployment including several rooms. The second topic is related to improving the data transfer reliability while still keep minimum energy consumption. This has led us to focus on the multi-hop mesh network topology with multi-constrained QoS routing problem (PhD thesis of Evangelia Tsiontsiou) [33]. The third topic is related to the wireless charging of sensor nodes (PhD work of Lei MO) in order to keeping sensors in perpetual working state. A new direction has been also investigated which consists in using the CSI (channel signal information) of the omnipresent WiFi (IEEE802.11n) as a new generation of contactless sensors. A first test bed of using CSI to measure the respiration rate has been set up.

8.2. National Initiatives

8.2.1. ANR BottleNet

Participants: Isabelle Chrisment [contact], Thibault Cholez, Vassili Rivron, Paul Andrey, Quentin Rouy.

The Quality of Experience (QoE) when accessing the Internet, on which more and more human activities depend, is a key factor for today's society. The complexity of Internet services and of user's local connectivity has grown dramatically in the last years with the proliferation of proxies and caches at the core and access technologies at the edge (home wireless and 3G/4G access), making it difficult to diagnose the root cause of performance bottlenecks. The objective of BottleNet is to deliver methods, algorithms, and software systems to measure end-to-end Internet QoE and to diagnose the cause of experienced issues. The result can then be used by users, network and service operators or regulators to improve the QoE.

The ANR BottleNet project (https://project.inria.fr/bottlenet) started this year with a kick-off on the 1st of February 2016. It involves many partners in the field of computer networks and QoE: Inria Muse and Diana teams, Lille1 University, Telecom Sud-Paris, Orange, IP-Label. The objective of BottleNet is to deliver methods, algorithms, and software systems to measure Internet QoE and diagnose the root cause of poor Internet QoE. Our goal calls for tools that run directly at users' devices. We plan to collect network and application performance metrics directly at users' devices and correlate it with user perception to model Internet QoE, and to correlate measurements across users and devices to diagnose poor Internet QoE. This data-driven approach is essential to address the challenging problem of modeling user perception and of diagnosing sources of bottlenecks in complex Internet services. BottleNet will lead to new solutions to assist users, network and service operators as well as regulators in understanding Internet QoE and the sources of performance bottleneck.

Our first research question was to evaluate the impact of web advertisement on users' QoE. An interdisciplinary approach was developed at MADYNES, by which we extend the common notion of "quality of information" on free news websites (usually based on journalistic content) to a notion of quality of experience for the user, that takes into account the degraded delivery of information by the multiplication of third party contents. We implemented a measurement tool as a web browser extension and made a dataset by browsing many news websites accessed with and without ad-blockers. The first statistical results retrieved from the dataset show that web-advertisement has a huge negative impact on QoE, for example multiplying the mean page load time by more than one order of magnitude and increasing the variance even more, while adblockers' profiles show faster and more uniform performances. These results have to be further refined but already show that web-advertisement, and more generally third-party content provider, play a huge role in poor Internet QoE and that it is a key parameter to investigate in the project. This study is leading to a structural analysis of the ad regulation mechanisms in the field of web journalism. Adblockers not only upgrades the QoE of visitors, but also contributes to define what "acceptable ads" should be.

This year the following task have been completed:

- Development of a platform to collect QoS & QoE on french news websites (Quentin Rouy, Telecom Nancy student). The first exploratory data collecting campaign measured the impact of Web Advertisement on client QoS, using FatHom plugin for Firefox (a tool from MUSE/Inria, partner of the BottleNet ANR project).
- Implementation of statistical treatment schemes (Paul Andrey, ENSAE student) to correlate QoS, economic models and adblocking effects on news websites.
- Preparation of a systematized measurement campaign on french and international news sites, in order to publish to a large audience.

8.2.2. ANR Doctor

Participants: Thibault Cholez [contact], Thomas Silverston [contact], Xavier Marchal, Cédric Enclos, Elian Aubry, Daishi Kondo, Olivier Festor.

The DOCTOR project http://www.doctor-project.org is an applied research project funded by the French National Research Agency (ANR), grant <ANR-14-CE28-000>, and supported by the French Systematic cluster. The project started on December 2014 for three years. It involves five partners specialized in network monitoring and security: Orange Labs (lead), Thales, Montimage, Université de technologie de Troyes and LORIA/CNRS. The DOCTOR project advocates the use of virtualized network equipment (Network Functions Virtualization), to enable the co-existence of new Information-Centric Networking stacks (e.g.: Named-Data Networking) with IP, and the progressive migration of traffic from one stack to the other while guaranteeing the good security and manageability of the network. Therefore in DOCTOR, the main goals of the project are: (1) the efficient deployment of NDN as a virtualized networking environment; (2) the monitoring and security of this virtualized NDN stack.

We presented the whole project at the IRTF Information-Centric Networking Research Group (ICNRG) in January.

This year, we made contributions in three critical points for the deployment of virtualized NDN network: security, performances and interoperability. First, we identified a critical vulnerability in the NDN protocol design that allows an attacker to perform efficient DoS attacks [46] by either self-answering to his own requests or answering to clients before the server. We proposed several remediation strategies to this problem.

On the performance topic, we designed and implemented a tool similar to Iperf, Ndnperf [22][0], that can measure the maximum throughput of a program serving NDN Data. We identified critical limitations that can harm real-time services (live streaming, VOIP, etc.), and proposed several recommendations and improvements that can increase the throughput up to 8 times when combined together.

Finally, we also designed and implemented an HTTP/NDN gateway that can be used to transport web content on an NDN network, thus benefiting from its caching and multicast properties while being totally transparent for the client and the server [47]. Those three contributions were published and demonstrated in the main conference of the domain: ACM ICN.

8.2.3. PIA LAR

Participants: Kévin Roussel, Ye-Qiong Song [contact].

LAR (Living Assistant Robot) is a PIA (Projet investissement d'avenir) national project getting together Inria (MAIA and MADYNES projects), *Crédit Agricole* (lead), Diatelic and Robotsoft. The aim is to develop an ambient assisted living system for elderly including both sensors and assistant robots. The task of Madynes team is the development of a WSN-based system integrating both sensors of the environment and sensors and actuators embedded on a mobile robot. The research issues include the QoS, energy and mobility management.

This project has ended in March 2016. Some new results are obtained including the use of Cooja simulator for RIOT OS based WSN simulation and an in-depth analysis of some timing inaccuracy problems introduced by MSPSim which is an emulator of MSP430 MCU [27]. A synthesis of our achievements on LAR project is reported in the PhD thesis of Kévin Roussel (http://www.theses.fr/196570603).

8.2.4. FUI HUMA

Participants: Jonathan Arnault, Giulia de Santis, Pierre-Olivier Brissaud, Jérôme François [contact], Abdelkader Lahmadi, Isabelle Chrisment.

The HUMA project (*L'HUmain au cœur de l'analyse de données MAssives pour la sécurité*) is funded under the national FUI Framework (Fonds Unique Interministeriel) jointly by the BPI (Banque Publique d'Investissement) and the Région Lorraine. It has been approved by two competitive clusters: Systematic and Imaginove. The consortium is composed of three academic (ICube, Citi, Inria) and five industrial (Airbus Defence and Space, Intrinsec, Oberthur, Wallix, Sydo) partners. The leader is Intrinsec.

This project targets the analysis of Advanced Persistent Threat. APT are long and complex attacks which thus cannot be captured with standard techniques focused on short time windows and few data sources. Indeed, APTs may be several months long and involve multiple steps with different types of attacks and approaches. The project will address such an issue by leveraging data analytics and visualization techniques to guide human experts, which are the only one able to analyze APT today, rather than targeting a fully automated approach.

In 2016, our contribution focused on defining a clustering technique in order to group individual events into a common one. We applied our technique to darknet data as shown in section 6.2.1. In addition, we also start the modeling of an attacker process by considering the first phase of APT, *i.e.* the reconnaissance phase by analyzing scanning activities using Hidden Markov Model in section 6.2.1. We also technically contribute to the definition of APT scenarios by providing a very stealthy scanning approach (Wiscan described in 6.1.2). Finally, from a project management point of view, Inria is in charge of leading the work-package related to data analytics technique for analyzing security probe events.

[0] http://madynes.loria.fr/software/ndnperf_cpp.zip

8.2.5. Inria-Orange Joint Lab

Participants: Jérôme François [contact], Rémi Badonnel, Olivier Festor, Maxime Compastié, Paul Chaignon.

The challenges addressed by the Inria-Orange joint lab relate to the virtualization of communication networks, the convergence between cloud computing and communication networks, and the underlying software-defined infrastructures. This lab aims at specifying and developing a GlobalOS (Global Operating System) approach as a platform or a software infrastructure for all the network and computing resources required by the Orange network operator. Our work, started in November 2015, concerns in particular monitoring methods for software-defined infrastructures, and management strategies for supporting software-defined security in multi-tenant cloud environments.

8.2.6. CNRS-INS2I PEPS NEFAE

Participants: Thibault Cholez [contact], Wazen Shbair, Isabelle Chrisment, Jérôme François.

The need to monitor the increasing proportion of HTTPS traffic while preserving the privacy of users led us to propose a privacy-preserving monitoring framework that allows efficient identification of encrypted traffic (based on full TLS sessions), without relying on any decryption (no HTTPS proxy). It is based on a new set of well-tuned network features to characterise the service inside the encrypted traffic and on machine learning algorithms. The CNRS PEPS founded NEFAE project aims to specifically address the practical challenges toward real time identification of encrypted traffic by developing a next-generation firewall prototype.

This year we first built and made publicly available a new HTTPS dataset[0] (with complete raw data) so that researchers can compare their identification algorithms. We also improved our HTTPS monitoring framework to allow real-time identification of HTTPS services with only a few data packets instead of the full TLS session. We show better performances that the related work in all dimensions: better accuracy, earlier decision and more fine-grained identification). A running prototype is also under development to evaluate the scalability and overhead of our solution.

8.2.7. CNRS-INS2I PEPS SURF

Participants: Abdelkader Lahmadi [contact], Jérôme François, Isabelle Chrisment.

The SURF project, funded by the CNRS PEPS program, addresses the challenge of a developing a methodology for the joint modelling and the analysis of the Cyber security and the safety of industrial systems in the context of the factory of the future. The project involves partners from the Heudiasyc Laboratory of the University of Technology of Compiègne (UTC), the CRAN laboratory and the Inria Madynes team. The goal of the project is to make a joint effort from safety and cyber security communities to address the challenges of a joint modelling of industrial systems while including attacks, vulnerabilities and failures. During the year 2016, with the partners of the project, we have mainly identified the key challenges regarding this issue where we identified the common models, metrics and analysis methods that should be built. We have also organized a scientific day (http://surf.loria.fr) with many industrials (EDF, PSA and Sentryo) and academic to share with them our work and clearly identify the requirement and experience regarding this issue. This short term project is ended by this year, however a consortium is established for further long term projects (ANR, FUI or H2020) to address the identified challenge of a joint analysis of the cyber security and the safety of industrial control systems.

8.2.8. ANR FLIRT

Participants: Olivier Festor [contact], Rémi Badonnel, Thibault Cholez, Jérôme François, Abdelkader Lahmadi, Laurent Andrey.

FLIRT (Formations Libres et Innovantes Réseaux & Télécom) is an applied research project leaded by the Institut Mines-Télécom, for a duration of 4 years. It includes 14 academic partners (engineering schools including Telecom Nancy), 3 industrial partners (Airbus, Nokia Group and Orange), 2 innovative startups (the MOOC agency, and Isograd), as well as 3 professional or scientific societies (Syntec Numérique, Unetel,

[0] http://betternet.lhs.loria.fr/datasets/https/

SEE). The project objective is to build a collection of 10 MOOCs (Massive Open Online Courses) in the area of networks and telecommunications, 3 training programmes based on this collection, as well as several innovations related to pedagogical efficiency (such as virtualization of practical labs, management of student cohorts, and adaptative assessment). The Madynes team is leading a working group dedicated to the building of a MOOC on network and service management. This MOOC will cover the fundamental concepts, architectures and protocols of the domain, as well as their evolution in the context of future Internet, and will include practical labs and exercises using widely-used tools and technologies.

8.2.9. Technological Development Action (ADT)

8.2.9.1. ADT UASS

The goal of this ADT is while still providing assistance in developing the Aetournos platform to help in the UAV Challenge Medical Express. Through this ADT, funded by Inria, Raphaël Cherfan has coordinated students work on the platform and tutoring the Aetournos team for the 2016 Outback Joe Search and Rescue / Medical Express Challenge, and help in the design and buidling of a novel Hybrid UAV.

8.2.9.2. ADT VERTEX

This ADT started on 2016 and will end on 2018. The Madynes project is a major partner funded at the level of 120k€. ADT VERTEX buildt upon the foundations of the Grid'5000 testbed aims to reinforce and extend it towards new use cases and scientific challenges. Several directions are being explored: networks and Software Defined Networking, Big Data, HPC, and production computation needs. Already developed prototypes are also being consolidated, and the necessary improvements to user management and tracking are also being performed.

8.2.9.3. ADT COSETTE

This ADT started on 2013 and is endind on 2016. The Madynes project is the only partner funded at the level of 120k€. ADT COSETTE, for *COherent SET of Tools for Experimentation* aims at developing or improving a tool suite for experimentation at large scale on testbeds such as Grid'5000. Specifically, we will work on (1) the development of Ruby-CUTE, a library gathering features useful when performing such experiments; (2) the porting of Kadeploy, Distem and XPFlow on top of Ruby-CUTE; (3) the release of XPFlow, developed in the context of Tomasz Buchert's PhD; (4) the improvement of the Distem emulator to address new scientific challenges in Cloud and HPC. E. Jeanvoine (SED) is delegated in the Madynes team for the duration of this project. A subsequent project is planned to start at the end of 2016 (ADT SDT).

8.2.9.4. ADT RIOT

RIOT ADT is a multi-site project with Infine and Madynes teams, which started in December 2016 for a duration of two years. The high-level objective is to (1) contribute open source code, upstream, to the RIOT code base, (2) coordinate RIOT development within Inria, with other engineers and researchers using/developing RIOT, (3) coordinate RIOT development outside Inria, help maintain the RIOT community at large (see http://www.riot-os.org and http://www.github.com/RIOT-OS/RIOT) which aims to become the equivalent of Linux for IoT devices that cannot run Linux because of resource constraints.

This year MADYNES team has mainly contributed to the efficient MAC layer protocol implementation issues. We have built a general MAC protocol module (gnrc mac module) for providing critical development tools for MAC protocol developers in the RIOT community (https://github.com/RIOT-OS/RIOT/pull/5941; https://github.com/RIOT-OS/RIOT/pull/5942; https://github.com/RIOT-OS/RIOT/pull/5949; https://github.com/RIOT-OS/RIOT/pull/5950; https://github.com/RIOT-OS/RIOT/pull/6069; https://github.com/RIOT-OS/RIOT/pull/6072). Based on these generic functions, we first contributed to the functionality and performance improvement of an universal example MAC protocol (Lw-MAC) (https://github.com/RIOT-OS/RIOT/pull/5941). We then implemented iQueue-MAC, which is a robust, energy efficient and traffic adaptive MAC protocol (https://github.com/RIOT-OS/RIOT/pull/5618). Currently, we have finished to implement most of the designed features of iQueue-MAC, such as the low duty-cycle scheme, the adaptive slots allocation scheme and the multi-channel operation. Experimental results collected from samr21-Xplained-pro boards showed that iQueue-MAC is robust and has a extremely low packet drop ratio, even when interference is strong.

8.2.10. Inria Project Lab

8.2.10.1. IPL BetterNet

Participants: Isabelle Chrisment [contact], Thibault Cholez, Vassili Rivron.

The Inria Project Lab BetterNet (https://project.inria.fr/betternet) launched in October 2016. Its goal is to build and deliver a scientific and technical collaborative observatory to measure and improve the Internet service access as perceived by users. We will propose new original user-centered measurement methods, which will associate social sciences to better understand Internet usage and the quality of services and networks. Tools, models and algorithms will be provided to collect data that will be shared and analyzed to offer a valuable service to scientists, stakeholders and civil society.

The Madynes team leads the IPL and in particular Isabelle Chrisment who coordinates the project. Several actions have already been done over the first months:

- Organization of the Kick-Off the 19th November in Paris;
- Recruitment of a shared PhD with SPYRALS (Inria/University of Lille3) in order to develop probes and collecting platform;
- Servers installation in LHS (High Security Laboratory) for the hosting of the different BottleNet and BetterNet data collection and opendata platforms;
- Preparation of small and middle scale QoE and QoS data collection with users. Conception of incentives and rewards (value added services).

8.3. European Initiatives

8.3.1. FP7 & H2020 Projects

8.3.1.1. Flamingo

Title: Management of the Future Internet

Programm: FP7

Duration: November 2012 - December 2016

Coordinator: University Twente

Partners:

Iminds Vzw (Belgium),
Jacobs University Bremen Ggmbh (Germany),
University College London (United Kingdom),
Université de Lorraine (France),
Universitaet Der Bundeswehr Muenchen (Germany),
Universitat Politecnica de Catalunya (Spain),
Universiteit Twente (Netherlands),
Universitaet Zuerich (Switzerland)

Inria contact: Jérôme François

The goals of FLAMINGO are (a) to strongly integrate the research of leading European research groups in the area of network and service management, (b) to strengthen the European and worldwide research in this area, and (c) to bridge the gap between scientific research and industrial application.

In 2016, our research activities in Flamingo have been focused on (a) the analysis and evaluation of OpenFlow message usage for security applications, in particular to enable fast deployment and reconfiguration of mitigation technique (6.2.4) in cooperation with Universitaet Der Bundeswehr Muenchen; (b) passive monitoring of Internet-of-Things using the RPL protocol in cooperation with the Jacobs University Bremen; (c) monitoring of HTTPS traffic to identify user services without necessity of decrypting (6.1.4) and (d) low-footprint Internet wide scanning using our WISCAN software developed last year.

We have pursued leading the standardization activities of the project (WP leader).

8.3.2. Collaborations in European Programs, Except FP7 & H2020

8.3.2.1. RETINA

Program: Eurosatrs-2

Project acronym: RETINA

Project title: Real-Time support for heterogenous networks in automotive applications

Duration: April 2016 - March 2018

Coordinator: TCN (Time critical networks)

Other partners: TCN (Sweden), Alkit (Sweden), Viktoria (Sweden), TNO (Netherlands), Scuola Superiore Sant'Anna (Italy), Evidence (Italy), University of Lorraine (France)

Abstract: The project will develop integrated software tools to predict, simulate, test and support real-time communication in heterogeneous vehicular networks. The tool set will allow SMEs and larger industry to design, develop and evaluate time-critical applications such as advanced safety systems and autonomous vehicles. This will put high requirements on both in-vehicle infrastructure, as well as vehicle-to-vehicle and vehicle-to infrastructure utilizing the next generation of mobile networks for ITS.

8.4. International Initiatives

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

8.4.1.1. IoT4D

Title: Internet of Things for Developping countries

International Partner (Institution - Laboratory - Researcher):

UY (Cameroon) - MASECNeSS - Thomas DJOTIO NDIE

Start year: 2016

We want connect wireless sensors networks to the Internet through gateways. Wireless network should have several acessible gateways (depending on the size and quality of service needed) and gateways should be used by several wireless sensors networks. This is an optimization problem in this perticular context, with unreliable communications and equipments that are easily disturbed by the environment

8.4.1.2. Masdin

Title: MAnagement of Software-Defined INfrastructure

International Partner (Institution - Laboratory - Researcher):

University of Luxembourg (Luxembourg) - SnT (Interdisciplinary Centre for Security, Reliability and Trust) - Radu State

Start year: 2016

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

Networking is deeply evolving with the rise of programmability and virtualization. The concept of SDI (Software-Defined Infrastructure) has emerged from SDN (Software-Defined Networking) and NFV (Network Function Virtualization) making thus the configuration of the network highly dynamic and adaptable in real-time. However, new methods and tools have to be defined to properly monitor and configure this type of infrastructure. Current works are mainly limited to apply former approaches of traditional network but do not exploit the novel capabilities offered by these technologies. The goal of the associate team is thus to define methodologies taking benefit of them for an efficient monitoring and use of SDI resources while investigating security issues it brings.

8.4.1.3. STIC-AmSud AKD Project

Participants: Rémi Badonnel [contact], Olivier Festor, Gaetan Hurel, Amedeo Napoli.

The AKD project, funded by the STIC-AmSud Program, addresses the challenge of autonomic knowledge discovery for security vulnerability prevention in self-governing systems. The partners include Federal University of Rio Grande do Sul (UFRGS, Brazil), Republic University of Uruguay (INCO, Uruguay), Technical University of Federico Santa Maria (UTFSM, Chile), and Inria (Orpailleur, Madynes). Computer vulnerabilities constitute one of the main entry points for security attacks, and therefore, vulnerability management mechanisms are crucial for any computer systems. However autonomic mechanisms for assessing and remediating vulnerabilities can degrade the performance of the system and might contradict existing operational policies. In that context, this project focuses on the design of solutions able to pro-actively understand the behavior of systems and networks, in order to prevent vulnerable states. For that purpose, our work concerns more specifically the exploitation and integration of knowledge discovery techniques within autonomic systems for providing intelligent self-configuration and self-protection. It also investigates the building of flexible and dynamic security management mechanisms taking benefits from software-defined methods and techniques.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. Member of the Organizing Committees

Rémi Badonnel was member of the organizing committee for the following conferences: IEEE International Conference on Network Softwarization (IEEE NetSoft 2016), IEEE/IFIP/In Assoc. with ACM SIGCOMM International Conference on Network and Service Management (IEEE/IFIP/In Assoc. with ACM SIGCOMM CNSM 2016), IEEE/IFIP International Symposium on Integrated Network Management (IEEE/IFIP IM 2017).

9.1.2. Scientific Events Selection

9.1.2.1. Chair of Conference Program Committees

Rémi Badonnel was TPC co-chair for the following conferences: the Experience Track of the IFIP/IEEE Network Operations and Management Symposium (IFIP/IEEE NOMS 2016), IFIP/IEEE International Workshop of Management of the Future Internet (IFIP/IEEE ManFI 2016), IFIP International Conference on Autonomous Infrastructure, Management and Security (IFIP AIMS 2016).

Isabelle Chrisment was TPC co-chair of the first IFIP Internet of People Workshop co-located with IFIP Networking 2016. She was member of the steering committee for RESSI'16 (Rendez-vous de la Recherche et de l'Enseignement de la Sécurité des Systèmes d'Information).

Olivier Festor was TPC co-chair of ACM/IEEE/IFIP Conference on Netwrk and Service Management (CNSM) 2016. He is also member of the steering committee (NISC) that coordinates the main conferences in network and service management (IM, NOMS, CNSM and AIMS). He was also Tutorial chair of IEEE Netsoft 2016 and workshop co-chair at IEEE/IFIP NOMS'2016.

9.1.2.2. Member of the Conference Program Committees

Rémi Badonnel: IFIP International Conference on Autonomous Infrastructure, Management and Security (IFIP AIMS 2016) ; IFIP/IEEE International Conference on Network and Service Management (IFIP/IEEE CNSM 2016) ; IEEE Global Information Infrastructure and Networking Symposium (IEEE GIIS 2016) ; IEEE Global Communications Conference (IEEE GLOBECOM - SAC 2016) ; IFIP/IEEE International Symposium on Integrated Network Management (IFIP/IEEE IM 2017).

Thibault Cholez: 2nd IEEE International Workshop on Security Testing and Monitoring (STAM 2016, IEEE ICDCS Workshop)

Isabelle Chrisment: IFIP International Conference on Autonomous Infrastructures, Management and Security (IFIP AIMS'16) ; Rencontres Francophones sur la Conception de Protocoles, l'évaluation de Performance et l'Expérimentation Aspects Algorithmiques de Télécommunications (CoResl'16) ; IEEE/IFIP International Workshop on Analytics for Network and Service Management (AnNet 2016) ; IEEE/IFIP International Symposium on Network Operations and Management (IEEE/IFIP NOMS'16).

Oliver Festor: IFIP/IEEE International Symposium on Integrated Network Management (IFIP/IEEE IM'2017) ; IEEE/IFIP Network Operations and Management Symposium 2016 ; IEEE Netsoft 2016 ; IEEE Asia Pacific NOMS'2016.

Jérôme François: IFIP International Conference on Autonomous Infrastructure, Management and Security (IFIP AIMS 2016) ; IEEE Global Information Infrastructure and Networking Symposium (IEEE GIIS 2016) ; Principles, Systems and Applications of IP Telecommunications (IPTComm'16) ; IFIP/IEEE International Workshop on Management of SDN and NFV Systems (IFIP/IEEE ManSDN 2016) ; Asia-Pacific Network Operations and Management Symposium (APNOMS 2016); IFIP/IEEE International Symposium on Integrated Network Management (IFIP/IEEE IM 2017).

Abdelkader Lahmadi: IFIP International Conference on Autonomous Infrastructure, Management and Security (IFIP AIMS 2016), PhD workshop ; Asia-Pacific Network Operations and Management Symposium (APNOMS 2016); IFIP/IEEE International Symposium on Integrated Network Management (IFIP/IEEE IM 2017); IEEE/IFIP International Workshop on Management of the Future Internet (ManFI 2016, held as part of IEEE/IFIP NOMS 2016); IEEE Conference on Network Softwarization (IEEE NetSoft 2016).

Ye-Qiong Song: IEEE International Workshop on Factory Communication Systems (WFCS 2016); IEEE International Conference on Communications and Networking (ComNet 2016) ; IEEE International Conference on Emerging Technologies and Factory Automation (ETFA 2016) ; 24th International Conference on Real-Time Networks and Systems (RTNS 2016) ; IEEE International conference on Telecommunications (ICT-2016) ; IFIP Wireless and Mobile Networking Conference (WMNC 2016).

Laurent Ciarletta: International Program Comittee, IEEE CSS / RAS International Conference on Unmanned Aircraft Systems ICUAS 2016.

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

Rémi Badonnel is Associate Editor for the Wiley International Journal of Network Management (IJNM).

Olivier Festor is an associate editor of IEEE Transactions on Networks and Systems Management (TNSM).

Ye-Qiong Song is an Associate Editor for the Elsevier Computers and Electrical Engineering journal, and for the Journal of Multimedia Information System.

9.1.3.2. Reviewer - Reviewing Activities

The following reviews for journals has been made by team members:

Rémi Badonnel: IEEE Transactions on Network and Service Management (IEEE TNSM), Springer Journal of the Network and Systems Management (JNSM), Wiley International Journal of Network Management (IJNM), IEEE Communications Magazine (COMMAG).

Thibault Cholez: Journal of Communications and Networks, Elsevier Computer Networks, IEEE Transactions on Network and Service Management, Elsevier Computers & Security, IEEE Global Communications Conference, IFIP/IEEE International Symposium on Integrated Network Management

Isabelle Chrisment: IEEE Transactions on Network and Service Management (IEEE TNSM), IEEE Communications Magazine (COMMAG), Wiley Security and Communication Networks (SCN).

Jérôme François: IEEE Transactions on Network and Service Management (IEEE TNSM), Springer Journal of Network and Systems Management, Elsevier Computer Networks Journal

Abdelkader Lahmadi: IEEE Transactions on Network and Service Management (IEEE TNSM); IEEE Communications Magazine (COMMAG); Springer Journal of Network and Systems Management (JNSM); Elsevier Journal of Computer Communications (COMCOM); Elsevier Journal of Engineering Applications of Artificial Intelligence (EAAI).

Ye-Qiong Song: Elsevier Computers and Electrical Engineering journal, Elsevier Ad hoc network journal, Journal of Real-time systems (Springer), IEEE Transactions on Industrial Informatics.

9.1.4. Invited Talks

Thibault Cholez:

- RESSI 2016, Toulouse: "Efficiently Bypassing SNI-based HTTPS Filtering"
- IRTF ICNRG, Paris: "Challenges and directions for the security management of ICN services"

Isabelle Chrisment:

- US-EU Workshop on the Next Generation Internet of Things, March 30-April, 2016, USC, Los Angeles, USA. "Security and Monitoring of (Every)Things"

Jérôme François:

- IRTF NMLRG (IETF 95), Buenos Aires, Argentina: "HTTPS Traffic Classification"
- IRTF NMLRG (colocated with EuCNC), Athens, Greece, " NML in Inria High Security Lab: overview and datasets"
- IRTF NMLRG (IETF 96), Berlin, Germany: "Malicious Domains: Automatic Detection with DNS Traffic Analysis"

Abdelkader Lahmadi:

- i-NOVIA (Salon of Nouvelle Technologies), Strasbourg, "Cybersecurity: monitoring and defense", 5 October 2016

9.1.5. Scientific Expertise

Laurent Ciarletta serves as expert for the 2016 ANR Generic call.

Jérôme François serves as reviewer for ANRT to evaluate a CIFRE PhD proposition

Ye-Qiong Song serves as reviewer for ANRT to evaluate a CIFRE PhD proposition.

Ye-Qiong Song serves as expert for "Fonds de recherche nature et technologies, Quebec".

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Rémi Badonnel is heading the Telecommunications, Networks and Services specialization of the 2nd and 3rd years at the TELECOM Nancy engineering school, and is coordinating the Security Pathway Program at the same school, elaborated in the context of the International Master of Science in Security of Computer Systems built with the Mines Nancy and ENSEM engineering schools.

Laurent Ciarletta is co-heading the specialization Safe Systems Architecture of the Computer Science and IT department of the Ecole des Mines de Nancy ("Grande Ecole", Engineering School, Master degree level).

Olivier Festor is the Director of the TELECOM Nancy Engineering School.

Team members are teaching the following courses:

Rémi Badonnel 242 hours - L3, M1, M2 - Networks, Systems and Services, Software Design and Programming, Cloud Computing, Network and Security Management - TELECOM Nancy, Université de Lorraine

Thibault Cholez 300 hours - L3, M1, M2 - Techniques and Tools for Programming, Computer Networks, Object-Oriented Programming, C and Shell Programming, Network Services, Constraint development on small Connected Objects, Mobile applications and Internet of Things - TELECOM Nancy, Université de Lorraine

Isabelle Chrisment 220 hours -L3, M1, M2 -C and Shell Programming, Computer Networking, Operating Systems, Network Security. - TELECOM Nancy, Université de Lorraine

Laurent Ciarletta 250 hours - M1, M2 - Networks and Services, Interactive Computing, Pervasive Comuting, Software Design and Programming, ARTEM - Mines Nancy - Ecole Nationale Superieure des Mines de nancy - Engineering school, Université de Lorraine, France

Jérôme François 70 hours - M1, M2 -Network security, Big Data - TELECOM Nancy, Université de Lorraine

Abdelkader Lahmadi 280 hours - L1, M1, M2 and Master Degree in Computer Science - Algorithms and Java programming, C language programming, Distributed algorithms, Sensor networks programming -ENSEM Engineering school, Université de Lorraine, France.

Ye-Qiong Song 230 hours - L1, M1, M2 Engineering degree and Master Degree in Computer Science - Algorithms and Java programming, Databases, Networking, Sensor networks - ENSEM - Engineering school, Université de Lorraine, France.

9.2.2. Supervision

9.2.2.1. PhD in progress in team

Elian Aubry, *Using Software Defined Network to manage Content Centric Networks*, since October 2013, supervised by Isabelle Chrisment & Thomas Silverston.

Pierre-Olivier Brissaud, *Anomaly detection in encrypted traffic*, since July 2016, supervised by Isabelle Chrisment, Jérôme François & Olivier Bettan (Thales)

Paul Chaignon, *Monitoring of SDN networks*, since July 2016, supervised by Olivier Festor, Jérôme François & Kahina Lazri (Orange Labs)

Maxime Compastie, *Software-Defined Security for the Cloud*, since Dec 2015, supervised by Olivier Festor & Rémi Badonnel.

Giulia De Santis, *Modelling and Analysis of Complex and Targeted Cyberattacks*, since October 2015, Olivier Festor & Abdelkader Lahmadi.

Meihui Gao, *Optimization models and methods for Network Functions Virtualization architectures*, since Nov 2015, supervised by Ye-Qiong Song & Bernardetta Addis.

Florian Greff, *QoS and fault-tolerance of distributed real-time systems over mesh networks*, since Feb. 2015, supervised by Ye-Qiong Song & Laurent Ciarletta.

Julien Vaubourg, *IP network models and simulators integration with DEVS for co-simulation of CPS*, since Oct. 2013, supervised by Vincent Chevrier & Laurent Ciarletta.

Thomas Paris, *Complex systems modeling using composition*, since Oct. 2015, supervised by Vincent Chevrier & Laurent Ciarletta.

Petro Aksonenko, *Optilized method of Calibration, Alignement and Advanced Attitude Algorithms for Strapdown Inertial Navigation Systems*, since Oct. 2016, supervised by Patrick Henaff, Anton Popov (KPI University) & Laurent Ciarletta

Patrick-Olivier Kamgue, *Routing management in WSNs*, since Jun 2012, supervised by Emmanuel Nataf & Olivier Festor in France, Thomas Djotio in Cameroun.

Daishi Kondo, *New Networking Architecture through Virtualization*, since September 2015, supervised with Olivier Perrin (EPI COAST) & Thomas Silverston.

Xavier Marchal, *Secure operation of virtualized Named Data Networks traffic*, since December 2015, supervised by Olivier Festor & Thibault Cholez.

Abdulqawi Saif, *Open Science for the scalability of a new generation search technology*, since December 2015, supervised by Ye-Qiong Song & Lucas Nussbaum.

Evangelia Tsiontsiou, *Multiconstrained QoS routing for wireless sensors networks with applications to smart space for ambient assisted living*, since Oct 2013, supervised by Ye-Qiong Song & Bernardetta Addis.

Shbair Wazen, *Service-level Monitoring of HTTPS*, since December 2013, supervised by Isabelle Chrisment & Thibault Cholez.

Nicolas Schnepf, *Orchestration and Verification of Security Functions for Smart Environments*, since October 2016, supervised by Stephan Merz, Rémi Badonnel & Abdelkader Lahmadi.

9.2.2.2. PhD defended in team

- [1] Tomasz Buchert, *Managing large-scale, distributed systems research experiments with control-flows*, *Université de Lorraine*, January 2016, supervised by Jens Gustedt & Lucas Nussbaum.
- Anthea Mayzaud, *Monitoring and Security for the Internet of Things*[0], *Université de Lorraine*, October 2016, supervised by Isabelle Chrisment & Rémi Badonnel.
- Kévin Roussel, *Dynamic management of QoS and energy in heterogeneous sensor networks for e-health applications*[0], June 2016, supervised by Ye-Qiong Song & Olivier Zendra.

9.2.3. Juries

Team members participated to the following Ph.D. defense committees in Computer Science if no other indication:

- Femke De Backere, in Computer Science from Ghent University, Belgium. Title: Design and Management of Pervasive eCare Services, June 2016 – (Rémi Badonnel as reviewer).
- Pasquale Puzio, PhD in Computer Science from TELECOM ParisTech, Sophia Antipolis, France. Title: Deduplication of Encrypted Data in Cloud Computing, February 2016 – (Isabelle Chrisment as examiner).
- Ziad Ismail, PhD in Computer Science from TELECOM ParisTech, Paris, France. Title: Optimal Defense Strategies to Improve the Security and Resilience of Smart Grids, April 2016 – (Isabelle Chrisment as reviewer).
- Erwan Godefroy, PhD in Computer Science from CentraleSupélec, Rennes, France. Title: *Définition et évaluation d'un mécanisme de génération de règles de corrélation liées à l'environnement*, September 2016 – (Isabelle Chrisment as president).
- Hiep Huu Nguyen, PhD in Computer Science from Université de Lorraine, Nancy, France. Title: Social Graph Anonymization, November 2016 – (Isabelle Chrisment as president).
- Chakadkit Thaenchaikun, PhD in Computer Science from Université de Toulouse, France. Title: Economie d'énergie en réseau filaire: Ingéniérie de trafic et mise en veille, November 2016 – (Isabelle Chrisment as reviewer).
- Kim Thuat Nguyen, PhD in Computer Science from Télécom SudParis, France. Title: Protocoles de sécurité efficaces pour les réseaux de capteurs IP sans-fil et l'Internet des Objets, December 2016 – (Isabelle Chrisment as reviewer).
- Mohamed Sabt, PhD in Computer Science from Université de Technologie de Compiègne, France. Title: Outsmarting Smartphones - Trust based on Provable Security and Hardware Primitives in Smartphones Architectures, December 2016 – (Isabelle Chrisment as examiner).

[0] registration not fully completed

[0] http://www.theses.fr/2016LORR0051

- Michal Krol, PhD. in Computer Science from University of Grenoble, Frace. Title: Routing in wireless sensor networks, March 2016 – (Olivier Festor as reviewer).
- Marc Bruyère, PhD. in Computer Science from University of Toulouse 3 - Paul Sabatier, France. Title: An outright open source approach for simple andpragmatic Internet eXchange, July 2016 – (Olivier Festor as reviewer).
- Ahmed Bouchami, PhD. in Computer Science from Universié de Lorraine. Title: Sécurité des ressources collaboratives dans les réseaux sociaux d'entreprise, July 2016. – (Olivier Festor as President).
- Benjamin Baron, PhD. in Computer Science from Pierre et Marie Curie Paris VI - Sorbonne Universités, France. Title: *Transport intermodalde données massives pour le délestage des réseaux d'infrastructure*, October 2016 – (Olivier Festor as examiner).
- Messaoud Aouadj, PhD. in Computer Science from University of Toulouse 3 - Paul Sabatier, France. Title: *AirNet: le modèle de virtualisation Edge-Fabric comme plan de contrôle poru les réseaux programmables*, November 2016. – (Olivier Festor as reviewer).
- Tiphaine Viard, PhD. in Computer Science from Pierre et Marie Curie - Sorbonne Universités, France. Title: *Flots de liens pour la modélisation d'interactions temporelles et application à l analyse de trafic IP*, September 2016 – (Olivier Festor as reviewer).
- Christoph Neumann, HDR in Computer Science from University of Rennes 1, France. Title: Contributions to Content Placement,Load-balancing and Caching: System Design and Security, November – 2016 (Olivier Festor as reviewer).
- Nadjib Ait Saadi, HDR in COMputer Science from University Paris Est Créteil, France. Title: From Sensors to Data Centers: Optimization of Deployment, Resource Allocation and Reliability, July 2016 – (Olivier Festor as President).
- Promethee Spathis, HDR in Computer Science from Pierre et Marie Curie - Sorbonne Universités, France. Title: Information DeliveryPast Struggles and New Directions, December 2016 – (Olivier Festor as reviewer).
- Hassan Said MOUSTAFA HARB, PhD. Université de Franche-Comté, France. Title: Energy Efficient Data Handling and Coverage for Wireless Sensor Networks, July 2016 – (Ye-Qiong Song as examiner).
- d'Abderrahmen Belfkih, PhD. Université du Havre, Title Contraintes temporelles dans les bases de données de capteurs sans fil, October 2016 – (Ye-Qiong Song as reviewer).
- Kawther Hassine, Ph.D. in ICT from Université de Carthage - SUPCOM Tunis. Title: Performance study of future wireless networks IEEE802.11 xy, December 2016 – (Ye-Qiong Song as reviewer).
- Lemia Louail, PhD. Université de Franche-Comté, Title: Approches cross-layer pour l'optimisation de la latence des communications dans les réseaux de capteurs sans fil, December 2016 – (Ye-Qiong Song as reviewer).
- Ahlem Mifdaoui, HDR. Université de Toulouse, Title: Contributions to Performance Analysis of Networked Cyber-Physical Systems, December 2016 – (Ye-Qiong Song as reviewer).

10. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] T. BUCHERT.*Managing large-scale, distributed systems research experiments with control-flows*, Université de Lorraine, January 2016, https://tel.archives-ouvertes.fr/tel-01273964.

Articles in International Peer-Reviewed Journal

[2] A. MAYZAUD, R. BADONNEL, I. CHRISMENT.*A Taxonomy of Attacks in RPL-based Internet of Things*, in "International Journal of Network Security", May 2016, vol. 18, n^o 3, p. 459 - 473,, https://hal.inria.fr/hal-01207859.

[3] Y. QI, P. CHENG, J. BAI, J. CHEN, G. ADRIEN, Y.-Q. SONG, Z. SHI.*Energy-Efficient Target Tracking by Mobile Sensors With Limited Sensing Range*, in "IEEE Transactions on Industrial Electronics", November 2016, vol. 63, n^o 11, 12 [*DOI :* 10.1109/TIE.2016.2584000], https://hal.inria.fr/hal-01403761.

Articles in National Peer-Reviewed Journal

[4] 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

[5] L. NUSSBAUM.*Chameleon, CloudLab, Grid'5000: What will the ultimate testbed look like?*, in "Grid'5000 Winter School 2016", Grenoble, France, February 2016, https://hal.inria.fr/hal-01274298.

[6] L. NUSSBAUM.*Deployment of Cloud stacks on Grid'5000*, in "GEFI Workshop", Brussels, Belgium, April 2016, https://hal.inria.fr/hal-01313210.

[7] L. NUSSBAUM.*Federating Grid'5000*, in "GEFI Workshop", Brussels, Belgium, April 2016, https://hal.inria.fr/hal-01313207.

[8] L. NUSSBAUM.*SDN/NFV experiments on Grid'5000*, in "GEFI Workshop", Brussels, Belgium, April 2016, https://hal.inria.fr/hal-01313204.

[9] L. NUSSBAUM.*Supporting Big Data experiments on Grid'5000*, in "GEFI Workshop", Brussels, Belgium, April 2016, https://hal.inria.fr/hal-01308370.

International Conferences with Proceedings

[10] E. AUBRY, T. SILVERSTON, I. CHRISMENT.*Croissance Verte dans NDN: Déploiement des Content Stores*, in "ALGOTEL 2016 - 18èmes Rencontres Francophones sur les Aspects Algorithmiques des Télécommunications", Bayonne, France, ALGOTEL 2016 - 18èmes Rencontres Francophones sur les Aspects Algorithmiques des Télécommunications, May 2016, https://hal.archives-ouvertes.fr/hal-01304444.

[11] E. AUBRY, T. SILVERSTON, I. CHRISMENT.*Green Growth in NDN: Deployment of Content Stores*, in "LANMAN 2016 - IEEE International Symposium on Local and Metropolitan Area Networks", Rome, Italy, Local and Metropolitan Area Networks (LANMAN), 2016 IEEE International Symposium on, IEEE, June 2016 [*DOI :* 10.1109/LANMAN.2016.7548850], https://hal.archives-ouvertes.fr/hal-01405820.

[12] A. BELKADI, D. THEILLIOL, L. CIARLETTA, J.-C. PONSART.*Robust flocking control design for a fleet of autonomous agents*, in "3rd Conference on Control and Fault-Tolerant Systems, SysTol 2016", Barcelone, Spain, September 2016, https://hal.archives-ouvertes.fr/hal-01348138.

[13] B. CAMUS, V. GALTIER, M. CAUJOLLE, V. CHEVRIER, J. VAUBOURG, L. CIARLETTA, C. BOURJOT.*Hybrid Co-simulation of FMUs using DEV&DESS in MECSYCO*, in "Symposium on Theory of Modeling & Simulation - DEVS Integrative M&S Symposium", Pasadena, CA, United States, Proceedings of the Symposium on Theory of Modeling & Simulation - DEVS Integrative M&S Symposium (TMS/DEVS 16), SCS/ACM (2016), April 2016, p. 568-575, https://hal.archives-ouvertes.fr/hal-01307616.

[14] L. CIARLETTA, L. FEJOZ, A. GUENARD, N. NAVET.*Development of a safe CPS component: the hybrid parachute, a remote termination add-on improving safety of UAS*, in "ERTS 2016 - 8th European Congress on Embedded Real Time Software and Systems", Toulous, France, January 2016, 10, https://hal.inria.fr/hal-01251305.

[15] L. CIARLETTA, T. GURRIET.*Towards a Generic and Modular Geofencing Strategy for Civilian UAVs*, in "2016 International Conference on Unmanned Aircraft Systems", Arlington, VA, United States, 2016 ICUAS Proceedings, June 2016, n^{o} 9781467393355, https://hal.inria.fr/hal-01398431.

[16] M. COMPASTIÉ, R. BADONNEL, O. FESTOR, R. HE, M. KASSI LAHLOU.*A Software-Defined Security Strategy for Supporting Autonomic Security Enforcement in Distributed Cloud*, in "IEEE International Conference on Cloud Computing Technology and Science (CloudCom'16), PhD Symposium", Luxembourg, Luxembourg, December 2016, 4, https://hal.inria.fr/hal-01399458.

[17] M. COUDRIAU, A. LAHMADI, J. FRANCOIS.*Topological Analysis and Visualisation of Network Monitoring Data: Darknet case study*, in "8th IEEE International Workshop on Information Forensics and Security - WIFS 2016", Abu Dhabi, United Arab Emirates, Information Forensics and Security, IEEE, December 2016, https://hal.inria.fr/hal-01403950.

[18] G. DE SANTIS, A. LAHMADI, J. FRANCOIS, O. FESTOR.*Modeling of IP scanning activities with Hidden Markov Models: Darknet case study*, in "8th IFIP International Conference on New Technologies, Mobility and Security", Larnaca, Cyprus, International Conference on New Technologies, Mobility and Security (NTMS), November 2016, https://hal.inria.fr/hal-01404127.

[19] L. DOLBERG, J. FRANCOIS, S. R. CHOWDHURY, R. AHMED, R. BOUTABA, T. ENGEL.*A Generic Framework to Support Application-Level Flow Management in Software-Defined Networks*, in "Conference on Network Softwarization (Netsoft)", Seoul, South Korea, IEEE, June 2016, https://hal.inria.fr/hal-01310574.

[20] J. FRANÇOIS, A. LAHMADI, V. GIANNINI, D. CUPIF, F. BECK, B. WALLRICH.*Optimizing Internet Scanning for Assessing Industrial Systems Exposure*, in "7th International Workshop on TRaffic Analysis and Characterization", Paphos, Cyprus, TRAC 2016 - 7th International Workshop on TRaffic Analysis and Characterization, September 2016 [*DOI :* 10.1109/IWCMC.2016.7577111], https://hal.inria.fr/hal-01371674.

[21] F. GREFF, E. DUJARDIN, A. SAMAMA, Y.-Q. SONG, L. CIARLETTA.*A Symbiotic Approach to Designing Cross-Layer QoS in Embedded Real-Time Systems*, in "8th European Congress on Embedded Real Time Software and Systems (ERTS 2016)"", Toulouse, France, January 2016, https://hal.inria.fr/hal-01242068.

[22] X. MARCHAL, T. CHOLEZ, O. FESTOR.*Server-side performance evaluation of NDN*, in "3rd ACM Conference on Information-Centric Networking (ACM-ICN'16)", Kyoto, Japan, ACM, September 2016, p. 148 - 153 [*DOI :* 10.1145/2984356.2984364], https://hal.inria.fr/hal-01386777.

[23] A. MAYZAUD, R. BADONNEL, I. CHRISMENT.*Detecting Version Number Attacks in RPL-based Networks using a Distributed Monitoring Architecture*, in "IEEE/IFIP/In Assoc. with ACM SIGCOMM International Conference on Network and Service Management (CNSM'12)", Montreal, Canada, October 2016, 9, https://hal.inria.fr/hal-01399432.

[24] A. MAYZAUD, A. SEHGAL, R. BADONNEL, I. CHRISMENT, J. SCHÖNWÄLDER.*Using the RPL Protocol for Supporting Passive Monitoring in the Internet of Things*, in "IEEE/IFIP Network Operations and Management Symposium", Istanbul, Turkey, April 2016, https://hal.inria.fr/hal-01247297.

[25] T. PARIS, A. TAN, V. CHEVRIER, L. CIARLETTA.*Study about decomposition and integration of continuous systems in discrete environment*, in "Annual Simulation Symposium (ANSS)", Pasadena, United States, Proceedings of the Annual Simulation Symposium (ANSS) 2016, April 2016, https://hal.inria.fr/hal-01256969.

[26] V. RIVRON, M. I. KHAN, S. CHARNEAU, I. CHRISMENT.*Exploring Smartphone Application Usage Logs with Declared Sociological Information*, in "Social computing and networking", Atlanta, United States, SocialCom 2016 : The 9th IEEE International Conference on Social Computing and Networking, IEEE, October 2016 [*DOI :* 10.1109/BDCLOUD-SOCIALCOM-SUSTAINCOM.2016.49], https://hal.inria.fr/hal-01378795.

[27] K. ROUSSEL, Y.-Q. SONG, O. ZENDRA.*Using Cooja for WSN Simulations: Some New Uses and Limits*, in "EWSN 2016 — NextMote workshop", Graz, Austria, K. ROEMER (editor), EWSN 2016 — NextMote workshop, Junction Publishing, February 2016, 319324, https://hal.inria.fr/hal-01240986.

[28] C. RUIZ, J. EMERAS, E. JEANVOINE, L. NUSSBAUM.*Distem: Evaluation of Fault Tolerance and Load Balancing Strategies in Real HPC Runtimes through Emulation*, in "CCGRID - 16th IEEE/ACM International Symposium on Cluster, Cloud and Grid Computing", Cartagena, Colombia, May 2016, https://hal.inria.fr/hal-00949762.

[29] S. SEEBER, R. GABI DREO, G. HUREL, R. BADONNEL.*Analysis and Evaluation of OpenFlow Message Usage for Security Applications*, in "IFIP International Conference on Autonomous Infrastructure, Management and Security (IFIP AIMS 2016)", Munich, Germany, Springer - Lecture Notes of Computer Science, June 2016, 12, https://hal.inria.fr/hal-01399439.

[30] W. M. SHBAIR, T. CHOLEZ, J. FRANÇOIS, I. CHRISMENT.*A Multi-Level Framework to Identify HTTPS Services*, in "IEEE/IFIP Network Operations and Management Symposium (NOMS 2016)", Istanbul, Turkey, IEEE, April 2016, p. p240-248 [*DOI :* 10.1109/NOMS.2016.7502818], https://hal.inria.fr/hal-01273160.

[31] W. M. SHBAIR, T. CHOLEZ, J. FRANÇOIS, I. CHRISMENT.*Improving SNI-based HTTPS Security Monitoring*, in "Second IEEE International Workshop on Security Testing and Monitoring", Nara, Japan, ICDCS 2016 - Workshops of the 36th IEEE International Conference on Distributed Computing Systems., IEEE, June 2016, 6, https://hal.inria.fr/hal-01349710.

[32] S. SIGNORELLO, R. STATE, J. FRANCOIS, O. FESTOR.*NDN.p4: Programming Information-Centric Data-Planes*, in "International Workshop on Open-Source Software Networking (OSSN), IEEE International Conference on Network Softwarization", Seoul, South Korea, June 2016, https://hal.inria.fr/hal-01310575.

[33] E. TSIONTSIOU, B. ADDIS, Y.-Q. SONG, A. CESELLI.*Optimal Probabilistic Energy-Aware Routing for Duty-Cycled Wireless Sensor Networks*, in "8th IFIP International Conference on New Technologies, Mobility and Security (NTMS 2016)", Larnaca, Cyprus, November 2016, https://hal.inria.fr/hal-01404169.

[34] J. VAUBOURG, V. CHEVRIER, L. CIARLETTA, B. CAMUS.*Co-Simulation of IP Network Models in the Cyber-Physical Systems Context, using a DEVS-based Platform*, in "Communications and Networking Simulation Symposium", Pasadena, United States, Proceedings of the Communications and Networking Simulation Symposium, ACM, 2016, Society for Computer Simulation International, https://hal.archives-ouvertes.fr/hal-01256907.

National Conferences with Proceeding

[35] A. SAIF, L. NUSSBAUM.*Performance Evaluation of NFS over a Wide-Area Network*, in "COMPAS - Conférence d'informatique en Parallélisme, Architecture et Système", Lorient, France, July 2016, https://hal.inria.fr/hal-01327272.

Conferences without Proceedings

[36] A. BELKADI, L. CIARLETTA, D. THEILLIOL.*UAVs fleet control design using distributed particle swarm optimization: A leaderless approach*, in "International Conference on Unmanned Aircraft Systems, ICUAS 2016", Arlington, VA, United States, June 2016, p. 364-371 [*DOI :* 10.1109/ICUAS.2016.7502679], https://hal.archives-ouvertes.fr/hal-01382063.

[37] D. I. MAXIM, R. DAVIS, L. I. CUCU-GROSJEAN, A. EASWARAN.*Probabilistic Analysis for Mixed Criticality Scheduling with SMC and AMC*, in "WMC 2016", Porto, Portugal, November 2016, https://hal.archives-ouvertes.fr/hal-01416310.

[38] L. NUSSBAUM.*Towards reproducibility of experiments*, in "Grid'5000 Winter School 2016 – Grid'5000 Scientific Advisory Board meeting", Grenoble, France, February 2016, https://hal.inria.fr/hal-01274293.

Books or Proceedings Editing

[39] R. BADONNEL, R. KOCH, A. PRAS, M. DRASAR, B. STILLER (editors). *Management and Security in the Age of Hyperconnectivity - Proceedings of the 10th IFIP International Conference on Autonomous Infrastructure, Management, and Security (AIMS 2016)*, Lecture Notes in Computer Science 9701, Springer - Lecture Notes of Computer Science, Munich, Germany, June 2016, https://hal.inria.fr/hal-01399447.

[40] J. WON-KI HONG, F. D. TURCK, J. KANG, H. CHOO, R. BADONNEL, B.-Y. CHOI, K. MYUNGSUP (editors). *Softwarization of Networks, Clouds, and Internet of Things - Proceedings of the 2nd IEEE International Conference on Network Softwarization (NetSoft 2016)*, Proceedings of the 2nd IEEE International Conference on Network Softwarization (NetSoft 2016), June 2016, https://hal.inria.fr/hal-01399452.

Research Reports

[41] B. CAMUS, V. GALTIER, M. CAUJOLLE, V. CHEVRIER, J. VAUBOURG, L. CIARLETTA, C. BOURJOT.*Hybrid Co-simulation of FMUs using DEV&DESS in MECSYCO*, Université de Lorraine, CNRS, Inria, LORIA, UMR 7503 ; CentraleSupélec UMI GT-CNRS 2958 Université Paris-Saclay ; EDF - R&D MIRE/R44, January 2016, https://hal.inria.fr/hal-01256738.

[42] B. CAMUS, T. PARIS, J. VAUBOURG, Y. PRESSE, C. BOURJOT, L. CIARLETTA, V. CHEVRIER.*MECSYCO: a Multi-agent DEVS Wrapping Platform for the Co-simulation of Complex Systems*, LORIA, UMR 7503, Université de Lorraine, CNRS, Vandoeuvre-lès-Nancy ; Inria Nancy - Grand Est (Villers-lès-Nancy, France), September 2016, https://hal.inria.fr/hal-01399978.

[43] C. RUIZ, E. JEANVOINE, L. NUSSBAUM.*Porting the Distem Emulator to the CloudLab and Chameleon testbeds*, Inria, September 2016, n° RR-8955, https://hal.inria.fr/hal-01372050.

Other Publications

[44] S. COOREVITS.*Fuzzing on the Openflow Protocol* , Telecom Nancy, September 2016, https://hal.inria.fr/hal-01386939.

[45] J. FRANCOIS, A. LAHMADI, M. DAVIDS, G. M. MOURA.*IPv6 DOTS Signal Option*, October 2016, IETF DOTS - Internet Draft, https://hal.inria.fr/hal-01406267.

[46] X. MARCHAL, T. CHOLEZ, O. FESTOR.*PIT matching from unregistered remote Faces: a critical NDN vulnerability*, ACM, September 2016, p. 211 - 212, 3rd ACM Conference on Information-Centric Networking (ACM-ICN'16), Poster [*DOI :* 10.1145/2984356.2985224], https://hal.inria.fr/hal-01386809.

[47] X. MARCHAL, M. EL AOUN, B. MATHIEU, W. MALLOULI, T. CHOLEZ, G. DOYEN, P. TRUONG, A. PLOIX, E. MONTES DE OCA.*A virtualized and monitored NDN infrastructure featuring a NDN/HTTP gateway*, ACM, September 2016, p. 225 - 226, 3rd ACM Conference on Information-Centric Networking (ACM-ICN'16), Poster [*DOI :* 10.1145/2984356.2985238], https://hal.inria.fr/hal-01386615.

[48] L. NUSSBAUM.*Usages et utilisateurs de Grid'5000: stratégie pour l'accès aux ressources*, March 2016, working paper or preprint, https://hal.inria.fr/hal-01294910.

[49] W. M. SHBAIR, T. CHOLEZ, J. FRANÇOIS, I. CHRISMENT.*HTTPS Traffic Classification*, April 2016, Network Machine Learning Research Group (NMLRG), Internet Research Task Force (IRTF), Buenos Aires, Argentina, April 2016, https://hal.inria.fr/hal-01392838.

References in notes

[50] O. FESTOR, A. LAHMADI, R. HOFSTEDE, A. PRAS.*Information Elements for IPFIX Metering Process Location*, July 2013, Internet Draft - IETF, https://hal.inria.fr/hal-00879567.

[51] N. FOSTER, A. GUHA, M. REITBLATT, A. STORY, M. J. FREEDMAN, N. PRAVEEN KATTA, C. MONSANTO, J. REICH, J. REXFORD, C. SCHLESINGER, D. WALKER, R. HARRISON.*Languages for software-defined networks*, in "IEEE Communications Magazine", 2013, vol. 51, n° 2, p. 128-134.

[52] J. SIEBERT.*Approche multi-agent pour la multi-modélisation et le couplage de simulations. Application à l'étude des influences entre le fonctionnement des réseaux ambiants et le comportement de leurs utilisateurs*, Université Henri Poincaré - Nancy I, September 2011, http://tel.archives-ouvertes.fr/tel-00642034.

Project-Team MAGRIT

Visual Augmentation of Complex Environments

IN COLLABORATION WITH: Laboratoire lorrain de recherche en informatique et ses applications (LORIA)

IN PARTNERSHIP WITH:
CNRS

Université de Lorraine

RESEARCH CENTER
Nancy - Grand Est

THEME
Vision, perception and multimedia interpretation

Table of contents

Project-Team MAGRIT

Creation of the Project-Team: 2006 April 03

Keywords:

Computer Science and Digital Science:

5.3. - Image processing and analysis
5.4. - Computer vision
5.4.1. - Object recognition
5.4.5. - Object tracking and motion analysis
5.4.6. - Object localization
5.6. - Virtual reality, augmented reality
5.10.2. - Perception

Other Research Topics and Application Domains:

2.6. - Biological and medical imaging
5.9. - Industrial maintenance
9.4.3. - Physics

1. Members

Research Scientists

Marie-Odile Berger [Team leader, Inria, Senior Researcher, HDR]
Erwan Kerrien [Inria, Researcher]

Faculty Members

Gilles Simon [Univ. Lorraine, Associate Professor]
Frédéric Sur [Univ. Lorraine, Associate Professor, HDR]
Pierre-Frédéric Villard [Univ. Lorraine, Associate Professor]
Brigitte Wrobel-Dautcourt [Univ. Lorraine, Associate Professor]

Technical Staff

Pierre-Jean Petitprez [Inria, until Sep 2016]

PhD Students

Charlotte Delmas [GE Healthcare, Cifre contract]
Antoine Fond [Univ. Lorraine]
Jaime Garcia Guevara [Inria, co-supervision with EPC MIMESIS]
Vincent Gaudilliere [Inria, from Dec 2016]
Pierre Rolin [Inria]
Raffaella Trivisonne [Inria, co-supervision with EPC MIMESIS]

Post-Doctoral Fellow

Cong Yang [Univ. Lorraine, from Oct 2016]

Administrative Assistants

Laurence Felicite [Univ. Lorraine]
Virginie Priester [CNRS, from Apr 2016]
Emmanuelle Deschamps [Inria]

Other

Mickaël Charles [Univ. Lorraine, Internship, from Mar 2016 until Jul 2016]

2. Overall Objectives

2.1. Augmented Reality

The basic concept of Augmented Reality (AR) is to place information correctly registered with the environment into the user's perception. What makes AR stand out is that this new technology offers the potential for big changes in many application fields such as industrial maintenance, creative technologies, image guided medical gestures, entertainment...

Augmented reality technologies have made major advancements recently, both in terms of capability, mobile development and integration into current mobile devices. Most applications are dedicated to multimedia and entertainment, games, lifestyle and healthcare and use rough localization information provided by the sensors of the mobile phones. Cutting-edge augmented reality applications which take place in complex environments and require high accuracy in augmentation are less prevalent. There are indeed still technological barriers that prevent applications from reaching the robustness and the accuracy required by such applications.

The aim of the MAGRIT project is to develop vision based methods which allow significant progress of AR technologies in terms of ease of implementation, reliability and robustness. An expected consequence is the widening of the current application field of AR.

The team is active in both medical and classical applications of augmented reality for which accurate integration of the virtual objects within the scene is essential. Key requirements of AR systems are the availability of registration techniques, both rigid and elastic, that allow the virtual objects to be correctly aligned with the environment, as well as means to build 3D models which are appropriate for pose computation and for handling interactions between the virtual objects and the real scene. Considering the common needs for tracking, navigation, advanced modeling and visualization technologies in both medical and industrial applications, the team focuses on three main objectives: matching, localization and modeling. Methods are developed with a view to meet the expected robustness and accuracy over time and to provide the user with a realistic perception of the augmented scene, while satisfying the real-time achievements required by these procedures.

3. Research Program

3.1. Matching and 3D tracking

One of the most basic problems currently limiting AR applications is the registration problem. The objects in the real and virtual worlds must be properly aligned with respect to each other, or the illusion that the two worlds coexist will be compromised.

As a large number of potential AR applications are interactive, real time pose computation is required. Although the registration problem has received a lot of attention in the computer vision community, the problem of real-time registration is still far from being a solved problem, especially for unstructured environments. Ideally, an AR system should work in all environments, without the need to prepare the scene ahead of time, independently of the variations in experimental conditions (lighting, weather condition,...) which may exist between the application and the time the model of the scene was acquired.

For several years, the MAGRIT project has been aiming at developing on-line and marker-less methods for camera pose computation. The main difficulty with on-line tracking is to ensure robustness of the process over time. For off-line processes, robustness is achieved by using spatial and temporal coherence of the considered sequence through move-matching techniques. To get robustness for open-loop systems, we have investigated various methods, ranging from statistical methods to the use of hybrid camera/sensor systems. Many of these methods are dedicated to piecewise-planar scenes and combine the advantage of move-matching methods and model-based methods. In order to reduce statistical fluctuations in viewpoint computation, which lead to unpleasant jittering or sliding effects, we have also developed model selection techniques which allow us to noticeably improve the visual impression and to reduce drift over time. Another line of research which has been considered in the team to improve the reliability and the robustness of pose algorithms is to combine the camera with another form of sensor in order to compensate for the shortcomings of each technology.

The success of pose computation over time largely depends on the quality of the matching at the initialization stage. Indeed, the current image may be very different from the appearances described in the model both on the geometrical and the photometric sides. Research is thus conducted in the team on the use of probabilistic methods to establish robust correspondences of features. The use of *a contrario* methods has been investigated to achieve this aim [8]. We especially addressed the complex case of matching in scenes with repeated patterns which are common in urban scenes. We are also investigating the problem of matching images taken from very different viewpoints which is central for the re-localization issue in AR. Within the context of a scene model acquired with structure from motion techniques, we are currently investigating the use of viewpoint simulation in order to allow successful pose computation even if the considered image is far from the positions used to build the model [4].

Recently, the issue of tracking deformable objects has gained importance in the team. This topic is mainly addressed in the context of medical applications through the design of bio-mechanical models guided by visual features [1]. We have successfully investigated the use of such models in laparoscopy, with a vascularized model of the liver and with a hyper-elastic model for tongue tracking in ultrasound images. However, these results have been obtained so far in relatively controlled environments, with non pathological cases. When clinical routine applications are to be considered, many parameters and considerations need to be taken into account. Among the problems that need to be addressed are more realistic model representations, the specification of the range of physical parameters and the need to enforce the robustness of the tracking with respect to outliers, which are common in the interventional context.

3.2. Image-based Modeling

Modeling the scene is a fundamental issue in AR for many reasons. First, pose computation algorithms often use a model of the scene or at least some 3D knowledge on the scene. Second, effective AR systems require a model of the scene to support interactions between the virtual and the real objects such as occlusions, lighting reflections, contacts...in real-time. Unlike pose computation which has to be computed in a sequential way, scene modeling can be considered as an off-line or an on-line problem depending on the requirements of the targeted application. Interactive in-situ modeling techniques have thus been developed with the aim to enable the user to define what is relevant at the time the model is being built during the application. On the other hand, we also proposed off-line multimodal techniques, mainly dedicated to AR medical applications, with the aim to obtain realistic and possibly dynamic models of organs suitable for real-time simulation.

In-situ modeling

In-situ modeling allows a user to directly build a 3D model of his/her surrounding environment and verify the geometry against the physical world in real-time. This is of particular interest when using AR in unprepared environments or building scenes that either have an ephemeral existence (e.g., a film set) or cannot be accessed frequently (e.g., a nuclear power plant). We have especially investigated two systems, one based on the image content only and the other based on multiple data coming from different sensors (camera, inertial measurement unit, laser rangefinder). Both systems use the camera-mouse principle [6] (i.e., interactions are performed by aiming at the scene through a video camera) and both systems have been designed to acquire polygonal textured models, which are particularly useful for camera tracking and object insertion in AR.

Multimodal modeling for real-time simulation

With respect to classical AR applications, AR in medical context differs in the nature and the size of the data which are available: a large amount of multimodal data is acquired on the patient or possibly on the operating room through sensing technologies or various image acquisitions [3]. The challenge is to analyze these data, to extract interesting features, to fuse and to visualize this information in a proper way. Within the MAGRIT team, we address several key problems related to medical augmented environments. Being able to acquire multimodal data which are temporally synchronized and spatially registered is the first difficulty we face when considering medical AR. Another key requirement of AR medical systems is the availability of 3D (+t) models of the organ/patient built from images, to be overlaid onto the users' view of the environment.

Methods for multimodal modeling are strongly dependent on the image modalities and the organ specificities. We thus only address a restricted number of medical applications –interventional neuro-radiology, laparoscopic surgery– for which we have a strong expertise and close relationships with motivated clinicians. In these applications, our aim is to produce realistic models and then realistic simulations of the patient to be used for surgeon's training or patient's re-education/learning.

One of our main applications is about neuroradiology. For the last 20 years, we have been working in close collaboration with the neuroradiology laboratory (CHU-University Hospital of Nancy) and GE Healthcare. As several imaging modalities are now available in an intraoperative context (2D and 3D angiography, MRI, ...), our aim is to develop a multi-modality framework to help therapeutic decision and treatment.

We have mainly been interested in the effective use of a multimodality framework in the treatment of arteriovenous malformations (AVM) and aneurysms in the context of interventional neuroradiology. The goal of interventional gestures is to guide endoscopic tools towards the pathology with the aim to perform embolization of the AVM or to fill the aneurysmal cavity by placing coils. We have proposed and developed multimodality and augmented reality tools which make various image modalities (2D and 3D angiography, fluoroscopic images, MRI, ...) cooperate in order to help physicians in clinical routine. One of the successes of this collaboration is the implementation of the concept of *augmented fluoroscopy*, which helps the surgeon to guide endoscopic tools towards the pathology. Lately, in cooperation with the team MIMESIS, we have proposed new methods for implicit modeling of the vasculature with the aim of obtaining near real-time simulation of the coil deployment in the aneurysm [2]. These works open the way towards near real-time patient-based simulations of interventional gestures both for training and for planning.

3.3. Parameter estimation

Many problems in computer vision or image analysis can be formulated in terms of parameter estimation from image-based measurements. This is the case of many problems addressed in the team such as pose computation or image-guided estimation of 3D deformable models. Often traditional robust techniques which take into account the covariance on the measurements are sufficient to achieve reliable parameter estimation. However, depending on their number, their spatial distribution and the uncertainty on these measurements, some problems are very sensitive to noise and there is a considerable interest in considering how parameter estimation could be improved if additional information on the noise were available. Another common problem in our field of research is the need to estimate constitutive parameters of the models, such as (bio)-mechanical parameters for instance. Direct measurement methods are destructive and elaborating image based methods is thus highly desirable. Besides designing appropriate estimation algorithms, a fundamental question is to understand what group of parameters under study can be reliably estimated from a given experimental setup.

This line of research is relatively new in the team. One of the challenges is to improve image-based parameter estimation techniques considering sensor noise and specific image formation models. In a collaboration with the Pascal Institute (Clermont Ferrand), metrological performance enhancement for experimental solid mechanics has been addressed through the development of dedicated signal processing methods [7]. In the medical field, specific methods based on an adaptive evolutionary optimization strategy have been designed for estimating respiratory parameters [9]. In the context of designing realistic simulators for neuroradiology, we are now considering how parameters involved in the simulation could be adapted to fit real images.

4. Application Domains

4.1. Augmented reality

We have a significant experience in AR that allowed good progress in building usable, reliable and robust AR systems. Our contributions cover the entire process of AR: matching, pose initialization, 3D tracking, in-situ modeling, handling interaction between real and virtual objects....

4.2. Medical Imaging

For 15 years, we have been working in close collaboration with University Hospital of Nancy and GE Healthcare in interventional neuroradiology. Our common aim is to develop a multimodality framework to help therapeutic decisions and interventional gestures. Contributions of the team focus on the developments of AR tools for neuro-navigation as well as the development of simulation tools for training or planning. Laparoscopic surgery is another field of interest with the development of methods for tracking deformable organs based on bio-mechanical models. Some of these projects are developed in collaboration with the MIMESIS project team.

4.3. Experimental mechanics

In experimental solid mechanics, an important problem is to characterize properties of specimen subject to mechanical constraints, which makes it necessary to measure tiny strains. Contactless measurement techniques have emerged in the last few years and are spreading quickly. They are mainly based on images of the surface of the specimen on which a regular grid or a random speckle has been deposited. We are engaged since June 2012 in a transdisciplinary collaboration with Institut Pascal (Clermont-Ferrand Université). The aim is to characterize the metrological performances of these techniques limited by, e.g., the sensor noise, and to improve them by several dedicated image processing tools.

5. New Software and Platforms

5.1. Ltrack

The Inria development action (ADT) LTrack aims at developing an Android platform in order to facilitate the transfer of some of our algorithms onto mobile devices. For the moment, the tracking-by-synthesis algorithm has been implemented (up to our knowledge, for the first time on a mobile device) in order to rigidly track a real object in real time assuming that a CAD model of this object is available. The design and implementation of the platform have been guided by the need to enable easy integration of any tracking algorithm based on combining video data and other sensor information.

- Contact: Marie-Odile Berger, Gilles Simon.

5.2. PoLAR

PoLAR (Portable Library for Augmented Reality) is a software library that offers powerful and state of the art visualization solutions under an API that is adapted and easy to use for a computer vision scientist. An ADT, also named PoLAR, started in October, 1st 2014 to sustain its development: a software engineer, Pierre-Jean Petitprez, was hired for two years. His contract ended at the end of September, 2016.

This year, the library was ported on Android, and Qt 5.7. Various diffusion media were also built: demos, e.g. linked with OpenCV; web site http://polar.inria.fr; detailed documentation with tutorials; and a paper was published at ISMAR'2016 conference [23].

PoLAR was made available to the public in October 2015, and can be used under Linux, Windows, MacOS and Android.

- Contact: Erwan Kerrien, Pierre-Frédéric Villard.
- URL: http://polar.inria.fr

5.3. Fast>VP

Fast>VP is a fast and effective tool to detect vanishing points in uncalibrated images of man-made environments and automatically orthorectify the involved planes. It is a Matlab implementation of the algorithm described in our Eurographics'2016 paper [25].

- Contact: Gilles Simon
- URL: https://members.loria.fr/GSimon/fastvp/

5.4. The GridMethod Toolbox

This Matlab toolbox implements several efficient and state-of-the art algorithms to estimate displacement and strain fields from grid images deposited on the surface of a specimen submitted to a loading or tensile test.

- Contact: Frédéric Sur
- URL:http://www.thegridmethod.net

6. New Results

6.1. Matching and localization

Participants: Marie-Odile Berger, Antoine Fond, Pierre Rolin, Gilles Simon, Frédéric Sur.

Pose initialization

Estimating the pose of a camera from a model of the scene is a challenging problem when the camera is in a position not covered by the views used to build the model, because feature matching is difficult in such a situation. Several viewpoint simulation techniques have been recently proposed in this context. They generally come with a high computational cost, are limited to specific scenes such as urban environments or object-centered scenes, or need an initial guess for the pose. In [24], we have proposed a viewpoint simulation method well suited to most scenes and query views. Two major problems have been addressed: the positioning of the virtual viewpoints with respect to the scene, and the synthesis of geometrically consistent patches. Experimental results showed that patch synthesis dramatically improves the accuracy of the pose in case of difficult registration, with a limited computational cost.

Facade detection and matching

Planar building facades are semantically meaningful city-scale landmarks. Such landmarks are essential for localization and guidance tasks in GPS-denied areas which are common in urban environments. Detection of facades is also key in augmented reality systems that allow for the annotation of prominent features in the user's view. We introduced several "facadeness" measures of image regions and showed how to combine them to generate building facade proposals in images of urban environments [26]. We demonstrated the interest of this procedure through two applications. First, a convolutional neural network (CNN) was proposed to detect facades from a restricted list of facade proposals. We showed that this method outperforms the state-of-the-art techniques in term of adequation of the detected facades with a ground truth. In addition, the computational time is compatible with the navigation requirements. Second, we investigated image matching based on facade proposals. Considering a large set of data extracted from Google Street View, we showed that matching based on Euclidean distances between CNN descriptors outperforms the classical SIFT matching based on RANSAC-homography calculation. This work has been submitted to IEEE ICRA'2017.

A preliminary step in facade detection is the image rectification process. For that purpose, we introduced a simple and effective method to detect orthogonal vanishing points in Manhattan scenes. A key element of this approach is to explicitly detect the horizon line *before* detecting the vanishing points, which is done by exploiting accumulations of oriented segments around the horizon line. This results in a significant reduction in computation times, while keeping an accuracy comparable or superior to more complex approaches. A paper reporting on this work was published and an oral presentation was made at Eurographics'2016 [25].

6.2. Handling non-rigid deformations

Participants: Marie-Odile Berger, Jaime Garcia Guevara, Pierre-Frédéric Villard.

Simultaneous pose estimation and augmentation of elastic surface

We have proposed an original method to estimate the pose of a monocular camera while simultaneously modeling and capturing the elastic deformation of the object to be augmented [22]. Our method tackles a challenging problem where ambiguities between rigid motion and non-rigid deformation are present. This issue represents a major barrier for the establishment of an efficient surgical augmented reality where the endoscopic camera moves and organs deform. Using an underlying physical model to estimate the low stressed regions our algorithm separates the rigid body motion from the elastic deformations using polar decomposition of the strain tensor. Following this decomposition, a constrained minimization, that encodes both the optical and the physical constraints, is resolved at each frame. Results on real and simulated data proved the effectiveness of our approach.

Fusing US and CT data

3D ultrasound (3D US) is an ideal imaging modality for hepatic image-guided interventions. Yet, its limited field of view and poor in-depth image quality reduce its usefulness. Within J. Guevara's PhD thesis, we propose to reduce these limitations by augmenting the intraoperative 3D US view with a preoperative image. Our approach is automatic and does not require manual initialization or a tracking device for the 3D US probe. Moreover, by using an underlying biomechanical model, the proposed method handles significant liver deformation, even when it occurs outside the 3D US field of view. The method relies on the segmentation of a vascular tree from the preoperative and intraoperative images, and their transformation into graphs. The preoperative and partial intraoperative graphs are then matched using an algorithm based on a combined Gaussian Process regression approach and biomechanical model. The model is used to robustly select a correct match from several hypotheses generated by the Gaussian Process. Once the two graphs are matched, a deformation of the preoperative liver is driven by the local displacement field computed from the partial graph match.

Individual-specific heart valve modeling

We developed a method to semi-automatically build a mitral valve computational model from micro CT (computed tomography) scans: after manually picking fiducial points on the chordae, the leaflets were segmented and the boundary conditions as well as the loading conditions were automatically defined. Fast Finite Element Method (FEM) simulation was carried out using Simulation Open Framework Architecture (SOFA) to reproduce leaflet closure at peak systole. We developed three metrics to evaluate simulation results. We validated our method on three explanted porcine hearts and showed that our model performs well. We evaluated the sensitivity of our model to changes in various parameters. We also measured the influence of the positions of the chordae tendineae on simulation results.

6.3. Interventional neuroradiology

Participants: Marie-Odile Berger, Charlotte Delmas, Erwan Kerrien, Raffaella Trivisonne.

Tools reconstruction for interventional neuro-radiology Minimally invasive techniques impact surgery in such ways that, in particular, an imaging modality is required to maintain a visual feedback. Live X-ray imaging, called fluoroscopy, is used in interventional neuroradiology. Such images are very noisy, and cannot show any brain tissue except the vasculature. In particular, since at most only two projective fluoroscopic views are available, containing absolutely no depth hint, the 3D shape of the micro-tool (guidewire, micro-catheter or micro-coil) can be very difficult, if not impossible to infer, which may have an impact on the clinical outcome of the procedure.

In collaboration with GE Healthcare, we aim at devising ways to reconstruct the micro-tools in 3D from fluoroscopy images. Charlotte Delmas has been working as a PhD CIFRE student on this subject since April 2013. A setup was designed in a view to reconstruct in 3D a deploying coil in as little X-ray dose and time as possible. It combines a fast rotation of both X-ray planes around the patient's head and a tomographic reconstruction combining an l_1-constraint to promote sparsity together with diffusion filters that promote the curvilinear nature of the coil. During this final year of her PhD thesis, various acquisition strategies and diffusion filters were evaluated [20].

Image driven simulation We consider image-driven simulation, applied to interventional neuroradiology as a coupled system of interactive computer-based simulation (interventional devices in blood vessels) and on-line medical image acquisitions (X-ray fluoroscopy). The main idea is to use the live X-ray images as references to continuously refine the parameters used to simulate the blood vessels and the interventional devices (micro-guide, micro-catheter, coil).

Raffaella Trivisonne started her PhD thesis in November 2015 (co-supervised by Stéphane Cotin, from MIMESIS team in Strasbourg) to address this research topic. Both projective and mechanical constraints were integrated in an augmented Lagrangian framework to solve the dynamical system. Experiments based on synthetic and phantom data were indicative that the shape from template problem could be solved without the need for considering collisions with the vessel surface, if an efficient tracking of the catheter in the X-ray images is available. These results were submitted for publication at a conference.

6.4. Assessing metrological performances in experimental mechanics

Participant: Frédéric Sur.

Progress was made during this year on several aspects of our collaboration with Institut Pascal on experimental mechanics. As mentioned in Section 4.3, the surface of the specimens under study are marked either by a regular grid, or by a random speckle. Displacement and strain maps are estimated by comparing images taken before and after deformation: through spectral methods (named here "the grid method") in the first case and through digital image correlation (DIC) in the latter.

Our contributions to the grid method are twofolds. First, we carefully analyzed the effect of digital sampling which causes aliasing [17]. We have proposed simple guidelines to minimize the effect of aliasing on strain maps. Second, we have mathematically characterized the properties of the analysis windows commonly used for processing grid images through the grid method [18]. It turns out that a Gaussian window has to be used, mainly because of its good concentration in both spatial and spectral domains in the sense of the Wigner-Ville transform. We eventually published a comprehensive review paper on the use of grid methods in experimental mechanics [15]

We also contributed to DIC-based methods. We have proposed new predictive formulas for the resolution of the displacement maps provided by DIC, which is mainly limited by sensor noise. These formulas take interpolation into account [12]. Indeed, displacement amplitude being often much smaller than one pixel, it is crucial to analyze the effect of the interpolation scheme. We have also proposed an experimental validation of these formula. This requires to take into account the heteroscedastic nature of sensor noise and rigid body motions caused by unavoidable vibrations [13].

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Grants with Industry

The partnership with GE Healthcare started in 1993. In the past few years, it bore on the supervision of CIFRE PhD fellows on the topic of using a multi-modal framework and augmented reality in interventional neuroradiology. A new PhD thesis -Charlotte Delmas- started in April 2013 with the aim to perform 3D reconstruction of tools in interventional neuroradiology. Our goal is to help clinical gesture by providing the physician with a better understanding of the relative positions of the tools and of the pathology.

8. Partnerships and Cooperations

8.1. Regional Initiatives

- Lorraine regional project about AR for liver surgery (2015-2018)
  The MAGRIT and the MIMESIS teams have been working for several years on the use of augmented reality for deformable organs and especially on liver surgery. The PhD of Jaime Garcia started in October 2015 and is funded by the Région Lorraine. It follows on from our past works and aims at improving the reliability and the robustness of AR-based clinical procedures.

8.2. National Initiatives

8.2.1. Projet RAPID EVORA

Participant: M.-O. Berger, V. Gaudillière, G. Simon.
This 3-year project is supported by DGA/DGE and led by the SBS-Interactive company. The objective is to develop a prototype for location and object recognition in large-scale industrial environments (factories, ships...), with the aim to enrich the operator's field of view with digital information and media. The main issues concern the size of the environment, the nature of the objects (often non textured, highly specular...) and the presence of repeated patterns. Use cases will be provided by industrial partners such as DCNS and Areva. A class of officer cadets and professors of the Merchant Marine School will also be associated to judge the pedagogical interest of such a tool. A PhD student, Vincent Gaudillière, has been recruited to work on this project and his contract started on 1rst December 2016.

8.2.2. Project funded by GDR ISIS in collaboration with Institut Pascal

Participant: F. Sur.
Since June 2012, we have been engaged in a collaboration with Pr. Michel Grédiac. The aim is to give a mathematical analysis and to help improving the image processing tools used in experimental mechanics at Institut Pascal.

The TIMEX project (2014-2016) is funded by GDR ISIS ("Appel à projet exploratoire, projet interdisciplinaire"). It aims at investigating image processing tools for enhancing the metrological performances of contactless measurement systems in experimental mechanics.

8.2.3. Collaboration with the MIMESIS team

Participants: R. Anxionnat, M.-O. Berger, E. Kerrien.
The SOFA-InterMedS large-scale Inria initiative is a research-oriented collaboration across several Inria project-teams, international research groups and clinical partners. Its main objective is to leverage specific competences available in each team to further develop the multidisciplinary field of Medical Simulation research. Our action within the initiative takes place in close collaboration with both the MIMESIS team and the Department of diagnostic and therapeutic interventional neuroradiology of Nancy University Hospital. We aim at providing in-vivo models of the patient's organs, and in particular a precise geometric model of the arterial wall. Such a model is used by the MIMESIS team to simulate the coil deployment within an intracranial aneurysm. The associated medical team in Nancy, and in particular our external collaborator René Anxionnat, is in charge of validating our results. For three years, we have also been collaborating with the MIMESIS team about real-time augmentation of deformable organs.

8.3. International Initiatives

8.3.1. Inria International Partners

8.3.1.1. Informal International Partners

Pierre-Frederic Villard has a "Harvard Affiliate" status through his collaboration with the Harvard Biorobotics Lab led by Professor Robert D. Howe. It follows a one year and a half sabbatical years (2014-2016) that Pierre-Frederic Villard spent in Harvard University in Cambridge (USA) working on heart valve modeling.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Selection

9.1.1.1. Member of the Conference Program Committees

- M.-O. Berger was member of the program committee of: International Conference on Medical Image Computing and Computer Assisted Intervention (MICCAI 2016), International Conference on Pattern recognition (ICPR 2016), International Conference on Robotic and automation (ICRA 2016), International Conference on Information Processing in Computer assited interventions (IPCAI 2017)
- Erwan Kerrien was a member of the program committee of MICCAI 2016 and of IPCAI 2017.
- F. Sur was a member of the program committe of RFIA 2016 (Reconnaissance des formes et intelligence artificielle).
- P.-F. Villard was member of the program committe of MICCAI 2016, International Conference on Computer Graphics, Visualization, Computer Vision and Image Processing 2016, Eurographics Workshop on Visual Computing for Biology and Medicine 2016.

9.1.1.2. Reviewer

M.-O. Berger was a reviewer for IROS 2016.

9.1.2. Journal

9.1.2.1. Reviewer - Reviewing Activities

The members of the team reviewed articles in Computers in Biology and Medicine (Elsevier), Digital Signal Processing, IEEE Transactions on Biomedical Engineering.

9.1.3. Invited Talks

- Pierre-Frédéric Villard gave a seminar on "Mitral Valve Biomechanical Model Construction" at the Department of Cardiac Surgery at Boston Children's Hospital, Boston (USA) on the 08/01/2016

9.1.4. Scientific Expertise

- Marie-Odile Berger was a member of the HCERES visiting commitee of LTSI (Rennes)
- Marie-Odile Berger was president of the AFRIF thesis prize and member of the GDR Robotique thesis prize.
- Marie-Odile Berger is president of the Association française pour la reconnaissance et l'interprétation des formes (AFRIF)

9.1.5. Research Administration

- Marie-Odile Berger is a member of the Inria evaluation committee.
- Gilles Simon is Chargé de Mission Loria to take part in an EIT's KIC (Knowledge and Innovation Communities) proposal in the thematic of manufacturing (KIC Added-value Manufacturing).

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

The four associate professors of the MAGRIT team actively teach at Université de Lorraine with an annual number of around 200 teaching hours in computer sciences, some of them being accomplished in the field of image processing. Inria researchers have ponctual teaching activities in computer vision and shape recognition mainly in the computer science Master of Nancy and in several Engineering Schools near Nancy (ENSMN Nancy, SUPELEC Metz, ENSG). Our goal is to attract Master students with good skills in applied mathematics towards the field of computer vision. The list of courses given by staff members which are tightly related to image processing and computer vision is detailed below:

- Licence: Graphic and haptic rendering, 30h, IUT Saint-Dié des Vosges.
- Licence: Image processing, 30h, IUT Saint-Dié des Vosges.
- Licence: 3D programming, 30h, IUT Saint-Dié des Vosges.
- Game design with Unity3D , 15h, IUT Saint-Dié des Vosges.
- Introduction to augmented reality, 6h, IUT Saint-Dié des Vosges.
- Master: Signal analysis, 50 h, Université de Lorraine.
- Master: Augmented reality, 24 h, Télécom-Nancy, Université de Lorraine.
- Master : Introduction to computer vision, 12h, Université de Lorraine.
- Master : Shape recognition, 15 h, Université de Lorraine.
- Master : Computer vision: foundations and applications, 15 h, Université de Lorraine.
- Master : Introduction to image processing, 21 h, École des Mines de Nancy
- Master : Image processing for Geosciences, ENSG, 12h.
- Master : Introduction to signal processing and applications, 21 h, Ecole des Mines de Nancy
- Master : Augmented reality, 24h, M2 IHM Metz
- Master : Augmented reality, 3 h, SUPELEC Metz.

In addition, G. Simon was interim director of the CESS (Centre d'Études Supérieures et Scientifiques) in Epinal, a branch of the science faculty of Nancy, from january to april 2016. He is also head of the Licence professionnelle Infographie Paysagère of the faculty of Nancy.

A software, named artEoz, has been co-designed by B. Wrobel-Dautcourt [21]. It aims at supporting students in learning computer programming. artEoz original design stems from the author's long term experience in teaching object oriented programming. It offers the students a pedagogical view of the memory state, that is dynamically updated while the user's program runs. artEoz can be freely downloaded for academic use only. This year, we have proposed an on-line version of the software. Documentation, tutorials, on-line tools and download are available on the website http://arteoz.loria.fr. Tutorials can be customized to fit different students' needs.

9.2.2. Supervision

PhD in progress: Pierre Rolin, Calcul de pose par simulation de points de vue pour la réalité augmentée, octobre 2013, Marie-Odile Berger, Frédéric Sur.

PhD in progress: Charlotte Delmas, Reconstruction 3D des outils chirurgicaux en radiologie interventionnelle, avril 2013, Marie-Odile Berger, Erwan Kerrien.

PhD in progress: Antoine Fond, Introduction de sémantique dans la modélisation urbaine dans un contexte de calcul du point de vue, octobre 2014, Marie-Odile Berger, Gilles Simon.

PhD in progress: Jaime Garcia Guevara, Vers une utilisation clinique de la réalité agmentée pour la chirurgie hépatique, octobre 2015, Marie-Odile Berger, Stéphane Cotin (MIMESIS).

PhD in progress: Raffaella Trivisonne, Image-guided real-time simulation using stochastic filtering, novembre 2015, Erwan Kerrien, Stéphane Cotin (MIMESIS).

PhD in progress: Vincent Gaudillière, Reconnaissance de lieux et d'objets pour la réalité augmentée en milieux complexes, décembre 2016, Marie-Odile Berger, Gilles Simon.

9.2.3. Juries

Marie-Odile Berger was external reviewer of the PhD of A. Bauer and A. Agustinos and of the HDR of R. Grompone. Gilles Simon was a member of the PhD committee of Liming Yang.

9.3. Popularization

Members of the team participate on a regular basis, to scientific awareness and mediation actions.

- Marie-Odile Berger and Gilles Simon wrote an article about augmented reality in Interstices [27].
- Erwan Kerrien is Chargé de Mission for scientific mediation at Inria Nancy-Grand Est. As such, he is a member of the steering committee of "la Maison pour la Science de Lorraine" [0], and member of the IREM [0] steering council. He also serves as the academic referent of an IREM working group aiming at introducing computer science in middle and high school curricula. Among other activites, he was also an associate researcher to a MATh.en.JEANS workshop, and he participated in the creation of a MOOC for teachers of the new ICN option (Informatique et Création Numérique - *Computer Science and Digital Creation*) at the beginning of high school curriculum.
- Gilles Simon participated to the "Fête de la science" (unplugged activities in computer science).
- Pierre-Frédéric Villard participated to open days and science festival in the IUT of Saint-Dié des Vosges. He presented augmented and virtual reality demos and their link to the high school mathematics program.
- Pierre-Frédéric Villard has been involved in the conception of the virtual visit for the Homo Numericus Exhibition (http://homonumericus.inria.fr).

10. Bibliography

Major publications by the team in recent years

[1] N. Haouchine, S. Cotin, I. Peterlik, J. Dequidt, M. Sanz-Lopez, E. Kerrien, M.-O. Berger.*Impact of Soft Tissue Heterogeneity on Augmented Reality for Liver Surgery*, in "IEEE Transactions on Visualization and Computer Graphics", 2015, vol. 21, n^{o} 5, p. 584 - 597 [*DOI :* 10.1109/TVCG.2014.2377772], https://hal.inria.fr/hal-01136728.

[2] E. Kerrien, A. Yureidini, J. D. Dequidt, C. Duriez, R. Anxionnat, S. Cotin.*Blood vessel modeling for interactive simulation of interventional neuroradiology procedures*, in "Medical Image Analysis", January 2017, vol. 35, p. 685 - 698 [*DOI :* 10.1016/j.media.2016.10.003], https://hal.inria.fr/hal-01390923.

[3] N. Padoy, T. Blum, A. Ahmadi, H. Feussner, M.-O. Berger, N. Navab.*Statistical Modeling and Recognition of Surgical Workflow*, in "Medical Image Analysis", 2011, http://hal.inria.fr/inria-00526493/en.

[4] P. Rolin, M.-O. Berger, F. Sur.*Viewpoint simulation for camera pose estimation from an unstructured scene model*, in "International Conference on Robotics and Automation", Seattle, United States, May 2015, https://hal.archives-ouvertes.fr/hal-01166785.

[5] G. Simon, M.-O. Berger.*Interactive Building and Augmentation of Piecewise Planar Environments Using the Intersection Lines*, in "The Visual Computer", February 2011, vol. 27, n^{o} 9, p. 827-841, http://hal.inria.fr/inria-00565129/en.

[6] G. Simon.*In-Situ 3D Sketching Using a Video Camera as an Interaction and Tracking Device*, in "31st Annual Conference of the European Association for Computer Graphics - Eurographics 2010", Suède Norrkoping, May 2010.

[0]"Houses for Science" project, see http://maisons-pour-la-science.org/en
[0]Institut de Recherche sur l'Enseignement des Mathématiques - *Research Institute for Teaching Mathematics*

[7] F. SUR, M. GREDIAC.*Measuring the Noise of Digital Imaging Sensors by Stacking Raw Images Affected by Vibrations and Illumination Flickering*, in "SIAM J. on Imaging Sciences", March 2015, vol. 8, n° 1, p. 611-643 [*DOI :* 10.1137/140977035], https://hal.inria.fr/hal-01133358.

[8] F. SUR, N. NOURY, M.-O. BERGER.*An A Contrario Model for Matching Interest Points under Geometric and Photometric Constraints*, in "SIAM Journal on Imaging Sciences", 2013, vol. 6, n° 4, p. 1956-1978 [*DOI :* 10.1137/120871766], http://hal.inria.fr/hal-00876215.

[9] F. P. VIDAL, P.-F. VILLARD, E. LUTTON.*Tuning of patient specific deformable models using an adaptive evolutionary optimization strategy*, in "IEEE Transactions on Biomedical Engineering", October 2012, vol. 59, n° 10, p. 2942 - 2949 [*DOI :* 10.1109/TBME.2012.2213251], https://hal.inria.fr/hal-00731910.

Publications of the year

Doctoral Dissertations and Habilitation Theses

[10] F. SUR.*Quelques contributions à l'analyse et au traitement des images numériques*, Université de Lorraine, November 2016, Habilitation à diriger des recherches, https://hal.archives-ouvertes.fr/tel-01399973.

Articles in International Peer-Reviewed Journal

[11] M. ARON, M.-O. BERGER, E. KERRIEN, B. WROBEL-DAUTCOURT, B. POTARD, Y. LAPRIE.*Multimodal acquisition of articulatory data: Geometrical and temporal registration*, in "Journal of the Acoustical Society of America", 2016, vol. 139, n° 2, 13 [*DOI :* 10.1121/1.4940666], https://hal.inria.fr/hal-01269578.

[12] B. BLAYSAT, M. GREDIAC, F. SUR.*Effect of interpolation on noise propagation from images to DIC displacement maps*, in "International Journal for Numerical Methods in Engineering", 2016, vol. 108, n° 3, p. 213-232 [*DOI :* 10.1002/NME.5212], https://hal.inria.fr/hal-01255944.

[13] B. BLAYSAT, M. GREDIAC, F. SUR.*On the propagation of camera sensor noise to displacement maps obtained by DIC - an experimental study*, in "Experimental Mechanics", 2016, vol. 56, n° 6, p. 919-944 [*DOI :* 10.1007/S11340-016-0130-9], https://hal.inria.fr/hal-01269655.

[14] M. GREDIAC, F. SUR, B. BLAYSAT.*Removing quasi-periodic noise in strain maps by filtering in the Fourier domain*, in "Experimental Techniques", 2016, vol. 40, n° 3, p. 959-971 [*DOI :* 10.1007/S40799-016-0100-2], https://hal.inria.fr/hal-01163838.

[15] M. GREDIAC, F. SUR, B. BLAYSAT.*The grid method for in-plane displacement and strain measurement: a review and analysis*, in "Strain", 2016, vol. 52, n° 3, p. 205-243 [*DOI :* 10.1111/STR.12182], https://hal.inria.fr/hal-01317145.

[16] E. KERRIEN, A. YUREIDINI, J. DEQUIDT, C. DURIEZ, R. ANXIONNAT, S. COTIN.*Blood vessel modeling for interactive simulation of interventional neuroradiology procedures*, in "Medical Image Analysis", January 2017, vol. 35, p. 685 - 698 [*DOI :* 10.1016/J.MEDIA.2016.10.003], https://hal.inria.fr/hal-01390923.

[17] F. SUR, B. BLAYSAT, M. GREDIAC.*Determining displacement and strain maps immune from aliasing effect with the grid method*, in "Optics and Lasers in Engineering", 2016, vol. 86, p. 317-328 [*DOI :* 10.1016/J.OPTLASENG.2016.06.010], https://hal.archives-ouvertes.fr/hal-01352868.

[18] F. SUR, M. GREDIAC.*Influence of the analysis window on the metrological performance of the grid method*, in "Journal of Mathematical Imaging and Vision", 2016, vol. 56, n^o^ 3, p. 472-498 [*DOI :* 10.1007/S10851-016-0650-Z], https://hal.inria.fr/hal-01298523.

[19] F. VIDAL, P.-F. VILLARD.*Development and Validation of Real-time Simulation of X-ray Imaging with Respiratory Motion*, in "Computerized Medical Imaging and Graphics", April 2016, vol. 49, 15 [*DOI :* 10.1016/J.COMPMEDIMAG.2015.12.002], https://hal.inria.fr/hal-01266065.

International Conferences with Proceedings

[20] C. DELMAS, C. RIDDELL, Y. TROUSSET, E. KERRIEN, M.-O. BERGER, R. ANXIONNAT, S. BRACARD.*Intra-operative 3D micro-coil imaging using subsampled tomographic acquisition patterns on a biplane C-arm system*, in "Proceedings of the 4th International Conference on Image Formation in X-Ray Computed Tomography (CT meeting'16)", Bamberg, Germany, July 2016, https://hal.inria.fr/hal-01303153.

[21] M. GAUTIER, B. WROBEL-DAUTCOURT.*artEoz - dynamic program visualization*, in "International Conference on Informatics in Schools: Situation, Evolution, and Perspectives, ISSEP 2016", Munster, Germany, October 2016, 2, https://hal.inria.fr/hal-01388703.

[22] N. HAOUCHINE, M.-O. BERGER, S. COTIN.*Simultaneous Pose Estimation and Augmentation of Elastic Surfaces from a Moving Monocular Camera*, in "International Symposium on Mixed and Augmented Reality", Merida, Mexico, September 2016, https://hal.inria.fr/hal-01353189.

[23] P.-J. PETITPREZ, E. KERRIEN, P.-F. VILLARD.*PoLAR: a Portable Library for Augmented Reality*, in "15th IEEE International Symposium on Mixed and Augmented Reality (ISMAR)", Merida, Mexico, IEEE , September 2016, 4, https://hal.inria.fr/hal-01356012.

[24] P. ROLIN, M.-O. BERGER, F. SUR.*Enhancing pose estimation through efficient patch synthesis*, in "27th British Machine Vision Conference (BMVC 2016)", York, United Kingdom, Proceedings of BMVC 2016, September 2016, https://hal.archives-ouvertes.fr/hal-01368843.

[25] G. SIMON, A. FOND, M.-O. BERGER.*A Simple and Effective Method to Detect Orthogonal Vanishing Points in Uncalibrated Images of Man-Made Environments*, in "Eurographics 2016", Lisbon, Portugal, May 2016, https://hal.inria.fr/hal-01275628.

National Conferences with Proceeding

[26] A. FOND, M.-O. BERGER, G. SIMON.*Generation of facade hypotheses based on contextual and structural information*, in "Reconnaissance des Formes et Intelligence Artificielle", Clermont Ferrand, France, June 2016, https://hal.inria.fr/hal-01318680.

Scientific Popularization

[27] M.-O. BERGER, G. SIMON.*Réalité augmentée : entre mythes et réalités*, in "Interstices", March 2016, https://hal.inria.fr/hal-01350456.

Team MIMESIS

Computational Anatomy and Simulation for Medicine

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
Nancy - Grand Est

THEME
Computational Neuroscience and Medecine

Table of contents

Team MIMESIS

Creation of the Team: 2015 July 01

Keywords:

Computer Science and Digital Science:

2.5. - Software engineering
3.1.1. - Modeling, representation
3.1.4. - Uncertain data
3.2.2. - Knowledge extraction, cleaning
5.1. - Human-Computer Interaction
5.3.4. - Registration
5.4.4. - 3D and spatio-temporal reconstruction
5.4.5. - Object tracking and motion analysis
5.6. - Virtual reality, augmented reality
6.1.1. - Continuous Modeling (PDE, ODE)
6.1.5. - Multiphysics modeling
6.2.8. - Computational geometry and meshes

Other Research Topics and Application Domains:

2.4. - Therapies
2.4.3. - Surgery
2.6. - Biological and medical imaging
2.7. - Medical devices
2.7.1. - Surgical devices

1. Members

Research Scientists

Stéphane Cotin [Team leader, Inria, Senior Researcher, HDR]
Hadrien Courtecuisse [CNRS, Researcher]
Igor Peterlik [Inria, Researcher]

Faculty Member

David Cazier [Université de Strasbourg, Professor, HDR]

Technical Staff

Rémi Bessard Duparc [Inria]
Bruno Marques [Inria]
Frederick Roy [Inria]
Etienne Schmitt [Inria]
Lionel Untereiner [Inria]

PhD Students

Rosalie Plantefève [Altran, until Jun 2016]
Christoph Paulus [Inria]
Raffaella Trivisonne [Inria]
Jaime Garcia Guevara [Inria]
Yinoussa Adagolodjo [Labex]

Post-Doctoral Fellows

Huu Phuoc Bui [Université de Strasbourg]
Nazim Haouchine [Inria]

Others

Arnaud Bonnet [Inria, Intern, from Jun 2016 until Sep 2016]
Jean-Nicolas Brunet [Inria, Intern, from Jun 2016]
Alexandre Dolle [Inria, Intern, from Mar 2016 until Aug 2016]
Mohamed Eissa [Inria, Intern, from Feb 2016 until Jun 2016]
Nicolas Gautier [Inria, Intern, from Mar 2016 un Jul 2016]
Lucile Hausser [Inria, Intern, from Jul 2016 until Aug 2016]
Sabrina Izcovich [Inria, Intern, form Jan 2016 until Mar 2016]
David John [Inria, Intern, until Jan 2016]
Roland Maier [Inria, Intern, from Sep 2016]
Thomas Massari [Inria, Intern, from Mar 2016 until Nov 2016]
Andréa Mendizabal [Inria, Intern, from Mar 2016 until Aug 2016]

2. Overall Objectives

2.1. Team Overview

At the end of 2011, a part of the SHACRA team moved from Lille to Strasbourg to join the newly created IHU institute, whose main objective is to develop novel clinical technologies at the crossroads of laparoscopic surgery, flexible endoscopy and interventional radiology. Similar institutes have been created in the past decade around the world, with the same global objective: create a synergy between clinicians and scientists to develop new technologies that can redefine healthcare, with a strong emphasis on clinical translation.

The scientific objectives of our new team, MIMESIS, are related to this ambitious objective. Over the past years we have developed new approaches supporting **advanced simulations in the context of simulation for training**. The best example of our success in this area was certainly the work done in collaboration with the HelpMeSee foundation, leading to the creation of our start-up InSimo.

We now propose to focus our research on the use of real-time simulation for per-operative guidance. The underlying objectives include *patient-specific biophysical modeling*, dedicated **numerical techniques for real-time computation**, data assimilation and **data-driven simulation**. This last topic is a transversal research theme and raises several open problems, ranging from non-rigid registration to augmented reality.

2.2. Challenges

The core research topics of the MIMESIS project-team essentially aim at improving the realism and fidelity of interactive simulations of medical procedures. This increase in realism makes it possible to envisage new clinical applications, in particular per-operative guidance, that currently rely on imaging techniques, but could greatly benefit from our expertise in real-time numerical simulation.

To reach these objectives we have identified several challenges that lie at the intersection of several scientific domains. They include the **modeling of complex anatomical environments** (to define new models describing soft tissue deformation or address coupled multi-physics problems), **novel numerical strategies** (to enable real-time computation even with the increase in complexity of future models), and **data-driven simulation** (to link simulation with real world data such as intra-operative images).

The SOFA framework is used to integrate our various contributions as a means to facilitate validation and technology transfer.

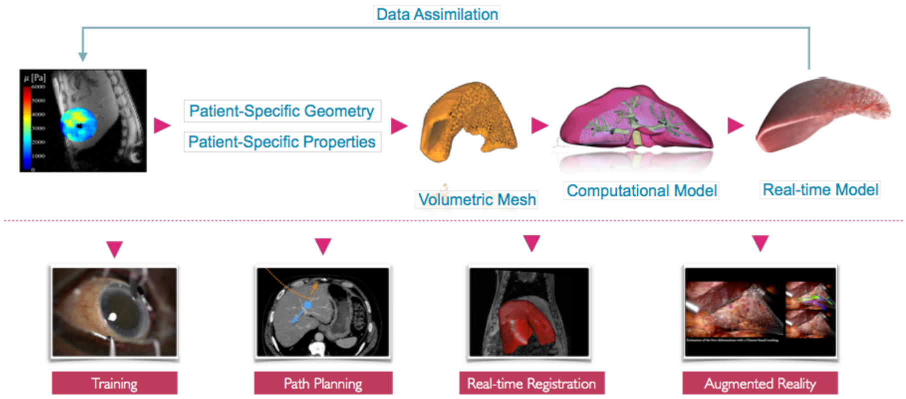

Figure 1. Patient-specific simulations: from training to intra-operative guidance

3. Research Program

3.1. Modeling of complex anatomical environments

Objectives:

- Coupled and multi-physics models & Non-linear and composite models
- Smooth and high-order FEM
- Hierarchical and heterogeneous representations

Milestones:

- Composite structures (e.g. vascularized organs)
- Integration of hyper-elastic materials and higher-order elements
- Combined behaviors (e.g. electro-mechanical model of the heart)

A central objective of this challenge is the modeling of the biomechanics and physiology of organs under various stimuli. This requires to describe different biophysical phenomena such as soft-tissue deformation, fluid dynamics, electrical propagation, or heat transfer. These models will help simulate the impact of different therapies (such as cryosurgery, radio-frequency ablation, surgical resection), but also represent the behavior of complex organs such as the brain, the liver or the heart (Figure 2).

A common requirement across these developments is the need for (near) real-time computation and the ability to adapt to patient-specific characteristics. Simulating such complex surgical environments involves the coupled use of composite models coming with their own discretizations that differ in terms of topology and dimension. This requires methods involving hierarchical or multi-resolution models that provide an inherent solution for the coupling of such heterogeneous representations. Another, related, objective is to study methods able to locally adapt the mesh resolution (when using an FEM approach) to the need of the simulation or to simulate the propagation of fractures during soft tissue tearing.

An important part of our research is dedicated to the development of new accurate models that remain compatible with real-time computation. Such advanced models not only permit to increase the realism of future training systems, but also act as a bridge toward the development of patient-specific preoperative planning as well as augmented reality tools for the operating room. Yet, patient-specific planning or per-operative guidance also requires the models to be parametrized with patient-specific biomechanical data. The objective in this area

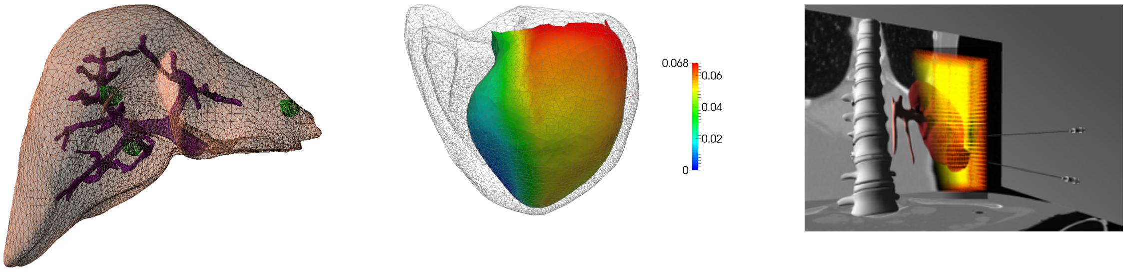

Figure 2. Left: patient-specific liver model with its vascular system. Middle: patient specific depolarization times. Right: cryoablation in the kidney.

is related to the study of hyper-elastic models and their validation for a range of tissues. Preliminary work in this area has been done through two collaborations, one with the biomechanical lab in Lille (LML), and the biomechanics group from the ICube laboratory in Strasbourg on the development and validation of liver and kidney models.

Another important research topic will be related to model reduction through various approaches, such as Proper Generalized Decomposition (PGD) or modal analysis. We are currently collaborationg with the Legato team at University of Luxembourg which has good expertise in this area. Similar approaches, such as the use of Krylov spaces, have already been studied in our group recently.

We are transitioning from our work on cardiac electro-physiology simulation to the modeling of the electrical conduction in soft tissues as well as optimization problems in the context of heat diffusion. This is a key element of the development of both planning and guidance systems for percutaneous procedures, such that an optimal therapeutical effect can be reached.

3.2. Numerical methods for real-time simulation

Objectives:

- Numerical solution of systems of equations
- Acceleration and optimization with parallel computing
- Context-aware discretization and adaptive (re)meshing for cuts and fractures
- Advanced constraints: Interaction, multi-body contacts - Collision detection

Milestones:

- Simulation of cutting, fracture and tearing
- Finite element simulation using adaptive meshing
- Mixed or hybrid finite element methods

The principal objective of this second challenge is to improve, at the numerical level, the efficiency, robustness, and quality of the simulations. To reach these goals, we essentially rely on two approaches: **adaptive meshing** to allow mesh transformations during a simulation and support cuts, local remeshing or dynamic refinement in areas of interest; and **numerical techniques**, such as asynchronous solvers, domain decomposition and model order reduction (Figure 3).

Typically, the simulations in the field of biomechanics, physiological modeling, or even computer graphics, employ techniques based on the finite element method. Such simulations require a discretization of the domain of interest, and this discretization is traditionally made of tetrahedral or hexahedral elements. The topology defined by these elements is also considered constant. The first objective of this work is to jointly develop advanced topological operations and new finite element approaches that can leverage the use of dynamic topologies. In particular we focus our research on multi-resolution meshes where elements are subdivided in areas where numerical errors need to be kept small [25], [27].

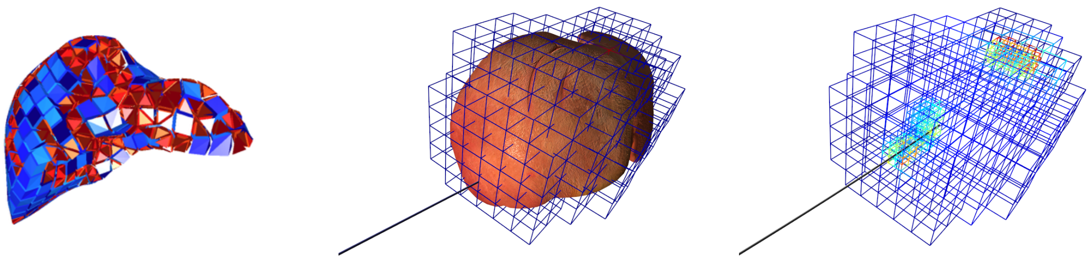

Figure 3. Left: Patient-specific mixed (tetrahedral + hexahedral) mesh of the liver. Middle: liver surface embedded into an hexahedral mesh. Right: dynamic subdivision of the mesh based on geometrical and mechanical constraints.

Once the problem, as defined in the previous challenge, has been discretized, we need to solve a large system of linear or nonlinear equations. In both cases, it is necessary to employ numerical solvers repeatedly to construct the solution representing the state of the simulated system. In the past years, we have contributed to this topic through our work on asynchronous preconditioning [19]. We would like to pursue this area of research exploiting the relevant advances in hierarchy-based topologies (e.g. the multi-grid methods). We will also consider advanced non-linear solvers which are necessary for correct resolution of hyper-elastic models and composite models.

Finally, to improve computational times from a programming stand-point, we have started a collaboration with the CAMUS team at Inria. This collaboration aims at using smart code analysis and on-the-fly parallelism to automatically speed-up computation times. In a typical scenario, the modeled organ or tissue is surrounded by its environment represented by other organs, connective tissues or fat. Further, during the intervention, the tissues are manipulated with instruments. Therefore, the interaction will also be an important aspect of our research. We have already developed methods for modeling of advanced interactions between organs, tissues and tools [24] [20]. We will continue exploiting novel methods such as partial factorization [28] and integrate our approach with other techniques such as augmented Lagrangian.

3.3. Data-driven simulation

Objectives:

- Stochastic filtering
- Inverse modeling
- Parametrization and estimation of the boundary conditions
- Validation and experimental assessment

Milestones:

- Non-rigid registration using biomechanical models
- Augmented reality for hepatic surgery
- 3D-2D real-time fusion for vascular surgery

Image-guided simulation has been a recent area of research in our team. We believe it has the potential to bridge the gap between medical imaging and clinical routine by adapting pre-operative data to the time of the procedure. Several challenges are related to image-guided therapy but the main issue consists in aligning pre-operative images onto the patient and keep this alignment up-to-date during the procedure. As most procedures deal with soft-tissues, elastic registration techniques are necessary to perform this step.

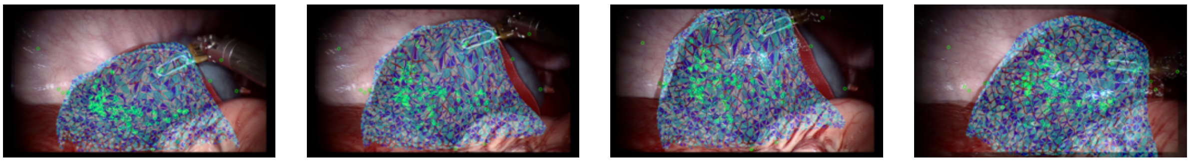

Figure 4. Real-time deformation of a virtual liver according to tissue motion tracked in laparoscopic images.

Recently, registration techniques started to account for soft tissue biomechanics using physically-based methods, yet several limitations still hinder the use of image-guided therapy in clinical routine. First, as registration methods become more complex, their computation times increase, thus lacking responsiveness. Second, techniques used for non-rigid registration or deformable augmented reality only "borrow" ideas from continuum mechanics but lack some key elements (such as identification of the rest shape, or definition of the boundary conditions). Also, these registration or augmented reality problems are highly dependent on the choice of image modality and require to investigate some aspects of computer vision or medical image processing. However, if we can properly address these challenges, the combination of a real-time simulation and regular acquisitions of image data during the procedure opens up very interesting possibilities by using data assimilation to better adapt the model to intra-operative data, not limited to image-based information.

In the area of non-rigid registration and augmented reality, we have already demonstrated the benefit of our physics-based approaches. This was applied in particular to the problem of organ tracking during surgery (Figure 4) and led to several key publications [22] [23] [21] and awards (best paper ISMAR 2013, second best paper at IPCAI 2014). We continue this work with an emphasis on robustness to uncertainty and outliers in the information extracted in real-time from image data and by improving upon our current computer vision techniques, in particular to guarantee a very accurate initial registration of the pre-operative model onto the per-operative surface patch extracted from monocular or stereo laparoscopic cameras. This work will finally benefit from advances in the challenges listed previously, in particular real-time hyper-elastic models of behavior.

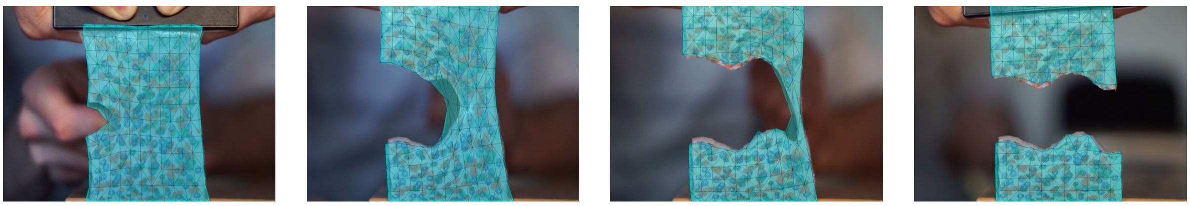

Figure 5. An augmented elastic object is torn. The cut is detected and applied to the virtual model in real time.

The use of simulation in the context of image-guided therapy can be extended in several other ways. A direction we are addressing is the combined use of simulation and X-ray imaging during interventional radiology procedures. Whether it is for percutaneous procedures or catheterization, the task of the simulation is to provide a short-term (1 to 5 seconds) prediction of the needle or catheter position. Using information extracted from the image, the parameters of the simulation can be assimilated (using methods such as unscented Kalman filters), so that the simulation progressively matches the real data in order to reduce uncertainties. We have already started to create a flexible framework integrating the real-time soft-tissue simulation and state-of-the-art methods of data assimilation and filtering.

4. New Software and Platforms

4.1. Simulation Open Framework Architecture

Keywords: Real time - Multi-physics simulation - Medical applications

Description: SOFA is an Open Source framework primarily targeted at real-time simulation, with an emphasis on medical simulation. It is mostly intended for the research community to help develop new algorithms, but can also be used as an efficient prototyping tool. Based on an advanced software architecture, it allows : the creation of complex and evolving simulations by combining new algorithms with algorithms already included in SOFA, the modification of most parameters of the simulation (deformable behavior, surface representation, solver, constraints, collision algorithm, etc.) by simply editing an XML file, the building of complex models from simpler ones using a scene-graph description, the efficient simulation of the dynamics of interacting objects using abstract equation solvers, the reuse and easy comparison of a variety of available methods.

URL: http://www.sofa-framework.org

5. New Results

5.1. Augmented Reality for Hepatic Surgery

Participants: Rosalie Plantefève, Bruno Marques, Frederick Roy, Nazim Haouchine, Igor Peterlik, Stéphane Cotin.

Liver cancer is the 2nd most common cause of cancer death worldwide, with more than 745,000 deaths from liver cancer in 2012. When including deaths from liver cirrhosis, the toll reaches nearly 2 million people worldwide. Today, surgical tumor ablation remains the best treatment for liver cancer.To localize the hepatic tumors and to define the resection planes, clinicians rely on pre-operative medical images (obtained with computed tomography scanner or magnetic resonance imaging). However, the liver lesions and vascular system are difficult to localize during surgery. This may lead to incomplete tumor resection or haemorrhage.

We provide surgeons with an augmented view of the liver and its internal structures during surgery to help them to optimally resect the tumors while limiting the risk of vascular lesion. Therefore, an elastic registration method to align the pre-operative and intra-operative data has been developed [26]. This method, which uses a biomechanical model and anatomical landmarks, was designed to limit its impact on the clinical workflow and reaches a registration accuracy below the resection margin even when the liver is strongly deformed between its pre-operative and intra-operative state. This registration algorithm has been integrated into a software, SOFA-OR, to conduct the first clinical tests.

5.2. Augmented Reality for Mini-Invasive Surgery

Participants: Nazim Haouchine, Lionel Untereiner, Frederick Roy, Igor Peterlik, Stéphane Cotin.

We have addressed the ill-posed problem of initial alignment of pre-operative to intra-operative data for augmented reality during minimally invasive hepatic surgery. This problem consists in finding the rigid transformation that relates the scanning reference and the endoscopic camera pose, and the non-rigid transformation undergone by the liver with respect to its scanned state. Most of the state-of-the-art methods assume a known initial registration.

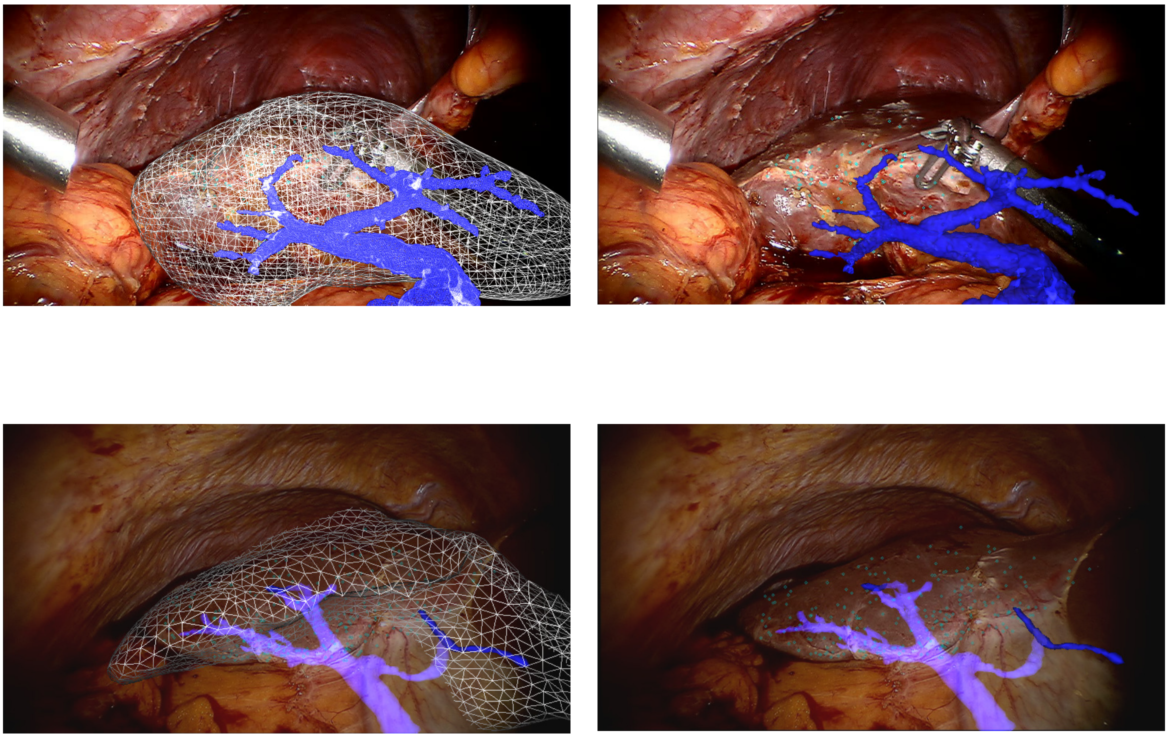

Figure 6. Non-rigid registration between intra-operative and pre-operative data. The overlay of the liver and its vascular network help the surgeon during the operation.

We have proposed in [16] a method that permits to recover the deformation undergone by the liver while simultaneously finding the rotational and translational parts of the transformation. Our formulation considers the boundaries of the liver with its surrounding tissues as hard constraints directly encoded in an energy minimization process. We performed experiments on real in-vivo data of human hepatic surgery and synthetic data, and compared our method with related works (Figure 7).

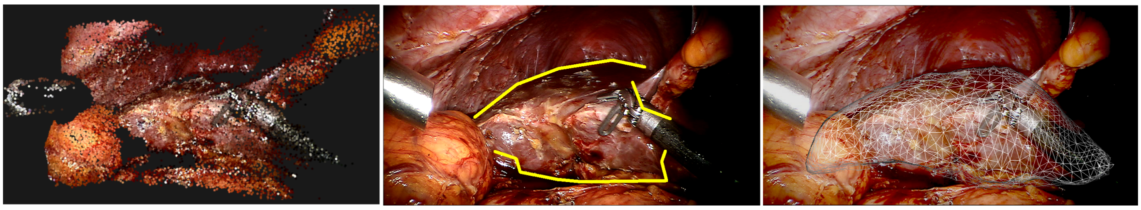

Figure 7. Left: a 3D map is reconstructed from the intra-operative view. Middle: The contours of the liver are extracted. Right: They are used as constraint to pilot a biomechanical model.

5.3. Detecting topological changes during non-rigid registration

Participants: Christoph Paulus, David Cazier, Stéphane Cotin.

Augmented reality has shown significant promise in overcoming certain visualization and interaction challenges in various domains such as medicine, construction, advertising, manufacturing, and gaming. Despite the promise of augmented reality and its successful application to many domains, significant research challenges remain. Among these challenges is the augmentation of non-rigid structures that can undergo topological changes, such as fracture, tearing or cutting. This is for instance the case in minimally invasive surgery, which has gained popularity and became a well-established procedure thanks to its benefits for the patient, in particular with shortened recovery times.

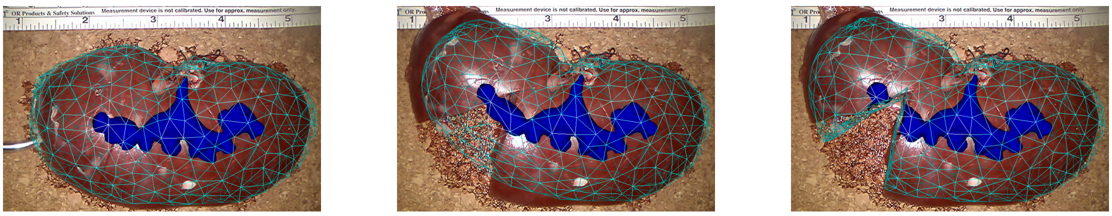

Figure 8. Left: A kidney whose internal structures have been scanned and segmented is cut and deformed. Middle: Standart methods do not detect the cut. Right: Our method detects the cut and applies it to the virtual model.

Current methods dealing with non-rigid augmented reality only provide an augmented view when the topology of the tracked object is not modified, which is an important limitation. We solve this shortcoming by introducing a method for physics-based non-rigid augmented reality [11]. Singularities caused by topological changes are detected by analyzing the displacement field of the underlying deformable model. These topological changes are then applied to the physics-based model to approximate the real cut. All these steps, from deformation to cutting simulation, are performed in real-time. This significantly improves the coherence between the actual view and the model, and provides added value.

5.4. Augmented Reality for Vascular Surgery

Participants: Raffaella Trivisonne, Igor Peterlik, Hadrien Courtecuisse, Stéphane Cotin.

Significant changes have taken place over the past 20 years in medicine with the development of minimally invasive procedures. While surgery evolved towards laparoscopy for instance, interventional radiology has become another alternative for many pathologies. Regarding catheter-based interventions, the lack of depth perception in projective grey-scale images, and the extensive use of X-ray imaging to visualize the instrument and the anatomy through which it must be inserted, are among the main issues. We propose to address these different problems by developing an advanced navigation system which relies on a combination of real-time simulation and information extracted from intra-operative images to assess the current position of the catheter. Such a method would have direct applications in endovascular procedures allowing for an enhanced view of the operating field, both in term of 3D perception and quality of the images. Our approach combines advanced modeling of the device, 2D-3D registration and constraint-based simulation.

We have developed a method [18] based on constraint-based simulation allowing for the enhancement of fluoroscopic images with a 3D real-time catheter insertion and 3D vessel visualization. Our method relies mainly on image features, without the need of any information about the surrounding 3D vasculature, nor does it require any tracking device (Figure 9).

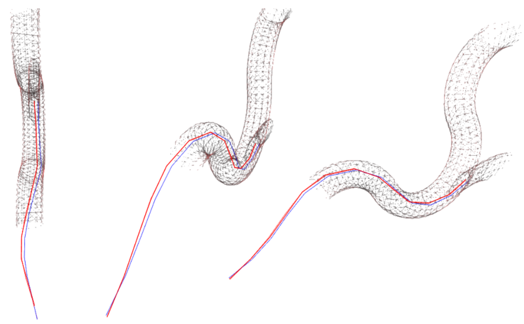

Figure 9. A 3D catheter reconstruction (red) and the real catheter (blue).

5.5. Image analysis for the characterization of cell mobility

Participant: Igor Peterlik.

The complex behaviour of motile cells plays a crucial role in biological processes such as tissue growth and tumorigenesis. Biomedical research that focuses on understanding the mechanisms of cell motility generates large amounts of multidimensional image data acquired by fully automated optical microscopes. Manual analysis of such data is extremely laborious and therefore, it is necessary to develop reliable automatic methods of image analysis. However, evaluation and assessment of such methods remains a challenging task, since in the case of real data, no ground truth is available to establish simple and robust metrics. Therefore, an important task in development of automatic methods of image analysis is the synthetic generation of realistic images allowing for quantitative assessment based on the ground truth.

We collaborate with the Centre of Biomedical Image Analysis (CBIA) at Masaryk University, Czech Republic on the development of reliable image analysis methods for quantitative characterization of cell motility driven by cellular protrusions at the leading edge of crawling cells. In particular, we develop physics-based models of living cells which are used to generate synthetic time-lapse 3D image series that realistically mimic the motile cells with protrusions (Figure 10). Although modeling of living cells has many specificities, we successfully exploit the modeling algorithms originally designed and developed for the simulation soft tissues. We have already demonstrated that realistic simulation of living cells can be achieved using SOFA and are working toward more complex models and scenarios, involving interactions among the cells and mitosis.

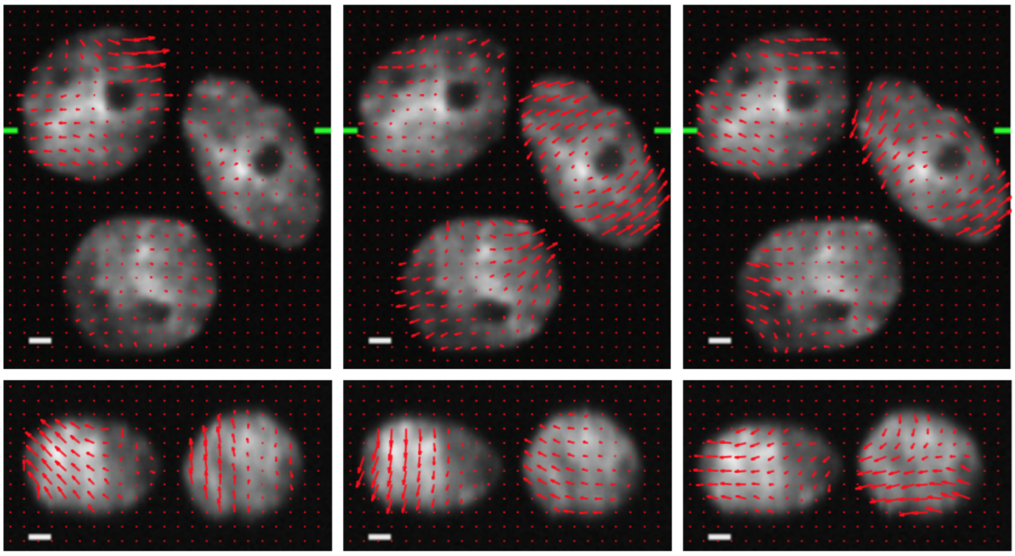

Figure 10. Sample synthetic nuclei generated with our method.

5.6. Training for retina surgery

Participants: Rémi Bessard Duparc, Stéphane Cotin.

Retina surgery is an increasingly performed procedure for the treatment of a wide spectrum of retinal pathologies. Yet, as most micro-surgical techniques, it requires long training periods before being mastered. To properly answer requests from clinicians for highly realistic training on one hand, and new requirements from accreditation or recertification from surgical societies on the other hand, we are developing a high-fidelity training system for retinal surgery.

This simulator is built upon our strong scientific expertise in the field of real-time simulation and a success story for technology transfer in the field of cataract surgery simulation. The simulation system is based on the Open Source simulation platform SOFA, and relies on expertise from our partners to ensure clinical and industrial relevance (this work is funded through the ANR project RESET). A first version of the training system has been developed and demonstrated in different ophthalmology conferences.

5.7. Robotic control of flexible needle insertion

Participants: Yinoussa Adagolodjo, Hadrien Courtecuisse.

We introduce a new method for automatic robotic needle steering in deformable tissues [13]. It uses an inverse Finite Element (FE) simulation to control an articulated robot interacting with deformable structures. We consider a flexible needle, embedded in the end effector of a 6 arm Mitsubishi RV1A robot, and its insertion into a silicone phantom. Given a trajectory on the rest configuration of the silicone phantom, our method provides in real-time the displacements of the articulated robot which guarantee the permanence of the needle within the predefined path, taking into account any undergoing deformation on both the needle

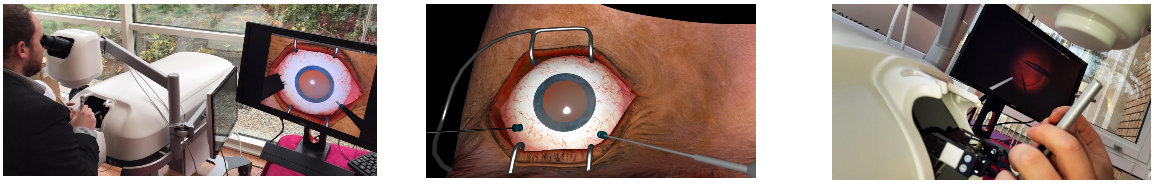

Figure 11. Left: the simulation is performed on a dedicated hardware including a microscope and instruments. Middle: The instruments are inserted in the eye. Right: The epiretinal membrane is removed.

and the trajectory itself. A forward simulation combines i) a kinematic model of the robot, ii) FE models of the needle and phantom gel iii) an interaction model allowing the simulation of friction and puncture force. A Newton-type method is then used to provide the displacement of the robot to minimize the distance between the needle's tip and the desired trajectory. We validate our approach with a simulation in which a virtual robot can successfully perform the insertion while both the needle and the trajectory undergo significant deformations.

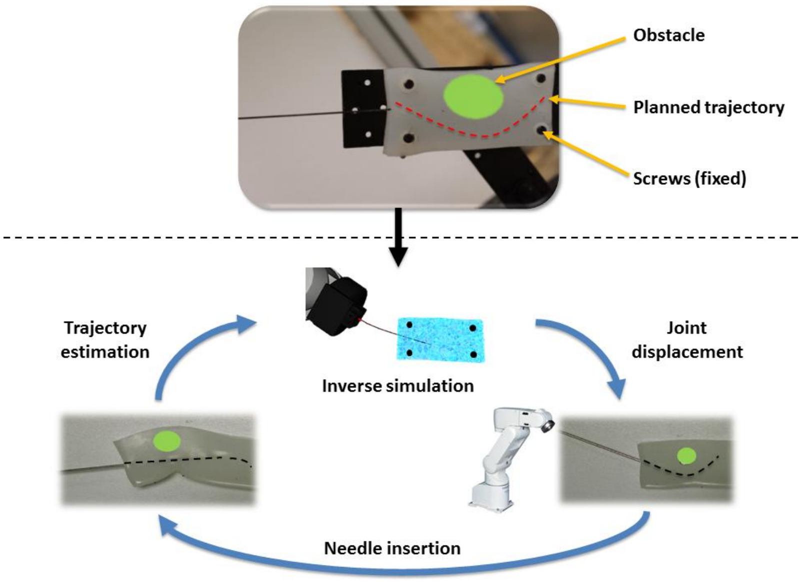

Figure 12. Automatic robotic needle steering in deformable tissues.

5.8. Compensation of brain shift in brain tumor surgery

Participant: Hadrien Courtecuisse.

During brain tumor surgery, planning and guidance are based on pre-operative images which do not account for brain-shift. However, this shift is a major source of error in neuro-navigation systems and affects the accuracy of the procedure. The vascular tree is extracted from pre-operative Magnetic Resonance Angiography and from intra-operative Doppler ultrasound images, which provides sparse information on brain deformations.

The pre-operative images are then updated based on an elastic registration of the blood vessels, driven by a patient-specific biomechanical model. We develop a biomechanical model [17] to extrapolate the deformation to the surrounding soft tissues. Our method has proved to efficiently compensate for brain deformation while being compatible with a surgical process.

5.9. Regional anaesthesia

Participants: Rémi Bessard Duparc, Stéphane Cotin.

The **RASimAs** project (Regional Anaesthesia Simulator and Assistant) is a European research project funded by the European Union's 7th Framework Program. It aims at providing a virtual reality simulator and assistant to doctors performing regional anaesthesia by developing the patient-specific Virtual Physiological Human models. Our work lead to the following journal article (submitted in Sept 2016) : *Real-time error controlled adaptive mesh refinement: Application to needle insertion simulation*.

This paper presents the first real-time discretization-error-driven adaptive finite element approach for corotational elasticity problems involving strain localization. We propose a hexahedron-based finite element method, combined with a posteriori error estimation driven local h-refinement, for simulating soft tissue deformation. This enables to control the local error and global error level in the mechanical fields (e.g. displacement or gradient) during the simulation. The local error level is used to refine the mesh only where it is needed, while maintaining a coarser mesh elsewhere. We investigate the convergence of the algorithm on academic examples, and demonstrate its practical usability on a percutaneous procedure involving needle insertion in soft tissues.

2016 was the third year of the project during which we developed new models of the biomechanics of the leg and arm, as well as the simulation of the insertion of the anaesthesiology needle.

See the RASimAs web site for more details.

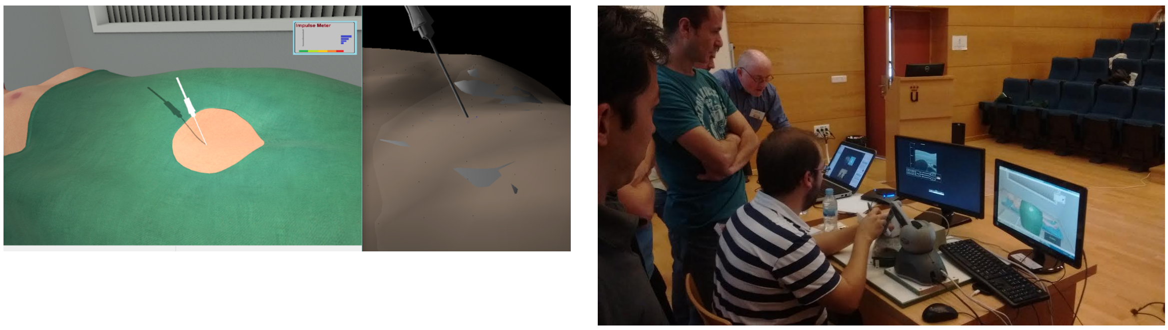

Figure 13. Left: Interface of the RASimAs simulator during femoral nerve block. Right: The RASimas developer team at the General Assembly.

6. Bilateral Contracts and Grants with Industry

6.1. Bilateral Contracts with Industry

The team is in close collaborations with:

InSimo is a startup we created in January 2013, after two years of thinking, maturation and incubation. Its founding members were all former team members of the SHACRA team (our previous team). The business model of the company is based on the SOFA platform and its community to transfer state-of-the-art simulation technologies into commercially-supported software components that medical simulator vendors can integrate into their products. The goal is to foster the creation of a new generation of medical simulators, highly realistic, faster to develop, allowing a broader commercial offer and novel uses. We collaborate with InSimo through the RESET ANR project.

In the context of the SOFA Consortium, the team is in close collaborations with:

Altran is a global leader in innovation and high-tech engineering consulting, Altran accompanies supports its clients in the creation and development of their new products and services. At the occasion of Altran internal scientific workshop, several members of the team (Rosalie Plantefève, Bruno Marques Jaime Guevara and Christoph Paulus) presented their work. We collaborate with Altran through the PhD thesis of Rosalie Plantefeve.

Anatoscope is a young start-up company created in 2015 by researchers, engineers and one surgeon. It develops a software solution to automatically build 3D digital avatars based on medical images of patients. The avatars allow biomechanical simulations of the real person.

TruPhysics develops Industry 4.0 software solutions to support manufacturing companies in development and sales processes by using a real-time and high-resolution physics simulation. We provide software that enables developers and engineers to simulate control programs, physical properties, kinematics and behavior of industrial robots, machines and assemblies. We collaborate with TruPhysics through the RASimAs FP7 project.

7. Partnerships and Cooperations

7.1. Regional Initiatives

7.1.1. Institut Hospitalo-Universitaire de Strasbourg

Our team has been selected to be part of the IHU of Strasbourg. This institute is a very strong innovative project of research dedicated to future surgery of the abdomen. It is dedicated to minimally invasive surgery, guided by image and simulation. Based on interdisciplinary expertise of academic partners and strong industry partnerships, the IHU aims at involving several specialized groups for doing research and developments towards hybrid surgery (gesture of the surgeon and simulation-based guidance). The MIMESIS team is an important part of the project. Since September 2011, we develop numerous experimental activities in close collaboration with clinicians.

7.1.2. Other research teams

At the regional level, the MIMESIS team also collaborates with:

Inria Magrit team: we closely collaborate with the Magrit team on the use of augmented reality in surgical procedures, through the PhD thesis of Jaime Garcia Guevara and the postdoctoral position of Nazim Haouchine. This collaboratin leads to many publications [14].

ICube *Automatique Vision et Robotique* (AVR) team: we are currently working with the medical robotics team on percutaneous procedures, in particular robotized needle insertion (with Prof. Bernard Bayle), and needle tracking in medical images (with Elodie Breton). We are also collaborating with Jonathan Vappou on elastography.

ICube *Informatique Géométrique et Graphqiue* (IGG) team: the Mimesis team joined the IGG team and develops collaboration in the domain of dynamic topologies, mainly through the use of the CGoGN framework. CGoGN is a C++ library for the manipulation of meshes. It implements combinatorial maps and their multiresolution extensions and has been used in various high level application like the simulation of crowds of autonomous agents and the simulation of cuts, tears and fractures in the context of surgical simulations.

Nouvel Hopital Civil, Strasbourg: since 2014 we have been working with Prof. David Gaucher, an ophthalmologist surgeon, expert in retina surgery. This led to the submission of the ANR project RESET which started in March 2015. We also collaborate with Prof. Patrick Pessaux, a surgeon who helps us in the context of the SOFA-OR project.

7.1.3. ADT: Aide au Développement Technologique

The MIMESIS receives support for the development of the SOFA framework through two ADT:

SofaOR (Jan 2015-Dec 2016): The objective of this ADT was twofold: first, we aimed at achieving a level of quality and robustness compatible with IEC 62304 for the core of SOFA and a reduced set of components. This does not include the certification of the code itself, but rather the implementation of a comprehensive development process that will enable the certification by companies wishing to integrate this code into their systems. The second objective was to add new features specific to the needs of using intra-operative guiding tools: interoperability with equipment from the operating room, acquisition and real-time processing of full HD video streams, data assimilation and predictive filters, path planning, visualization for augmented reality, or user interfaces dedicated to the operating room.

DynMesh (Sep 2015-Aug 2017): The objectives of this ADT was the coupling of SOFA, the physical simulation platform supported by Inria, and CGoGN, the mesh management library developed within the ICube lab at Strasbourg. The goal is to extend the physical engine SOFA with the topological kernel of CGoGN that supports a wide variety of mesh and many local remeshing operations. The coupling of both software libraries will provide users of physical engines with new tools for the development of simulations involving topological changes like cutting, fracturing, adaptation of the resolution or improving contact management or collision detection. The impacts are numerous and will be operated directly within the MIMESIS Team, with our partners or through the establishment of new collaborations.

7.2. National Initiatives

7.2.1. ANR

MIMESIS participates to the following ANR project:

RESET: This project started in March 2015 and will end in May 2017. Its objective is to develop a high-fidelity training system for retinal surgery. Retina surgery is an increasingly performed procedure for the treatment of a wide spectrum of retinal pathologies. Yet, as most micro-surgical techniques, it requires long training periods before being mastered. This simulator is built upon our scientific expertise in the field of real-time simulation, and our success story for technology transfer in the field of cataract surgery simulation (MSICS simulation developed for the HelpMeSee foundation).

Coordinator: MIMESIS

Partners: the InSimo company, the AVR team of the ICube lab.

7.2.2. National Collaborations

At the national level, the MIMESIS team collaborates with:

The LML laboratory *(Laboratoire de Mécanique de Lille)*: a French research laboratory (UMR CNRS 8107) part of the Carnot institute ARTS. With more than two hundred researchers, LML focuses on the following research areas: mechanical reliability and Tribology, fluid mechanics, civil engineering and soil mechanics.

The TIMC laboratory *(Techniques de l'Ingénierie Médicale et de la Complexité)* in Grenoble: this large research group has a strong background in computer-aided surgery, medical imaging, registration, statistical and bio-mechanical modeling. We have regular interactions with various members of this group. We are collaborating with Yohan Payan (DR CNRS) on the modeling and simulation of the brain shift. A common PhD thesis started on that topic in late 2014. Other areas of interest are in the field of advanced soft tissue modeling and computer aided surgery,

7.3. European Initiatives

7.3.1. FP7 & H2020 Projects

MIMESIS participates to the following European project:

Program: FP7

Project acronym: **RASimAs**

Project title: Regional Anaesthesia Simulator and Assistant

Duration: Nov 2013 - Nov 2016

Coordinator: Department of Medical Informatics, Uniklinik RWTH Aachen (Germany)

Other partners: we collaborate, among others, with: the University Hospital Aachen, RWTH Aachen, Bangor University, University College Cork, Universidad Rey Juan Carlos, Foundation for Research and Technology Hellas, Zilinska univerzita v Ziline, Katholieke Universiteit Leuven and the Stiftelsen Sintef.

Abstract: The goal of this project was to increase the application, the effectiveness and the success rates of regional anaesthesia and furthermore the diffusion of the method into a broader clinical use through the development of clinical tools to train new anaesthesiologists and assist them during the operation. The project combine two independent but complementary systems: one system is for training and the other one is for operational guidance. The training system consists in one medical simulator recreating RA operation for the anaesthesiologist in a virtual reality environment. The trainee is able to practise virtually the operation on various patient anatomies. The guidance system consists in assisting anaesthesiologists during the practise of RA by providing enhanced feedback on image interpretation and patient-specific anatomy. These two prototypes have been evaluated through a multi-centre clinical trial in Germany, Belgium and Ireland.

7.4. International Initiatives

The MIMESIS team has collaboration with the following international partners:

- **Team Legato, University of Luxembourg**: since last year we have active collaborations with Prof. Stéphane Bordas on real-time soft tissue cutting simulation. This has already led to a journal article [19] and the co-supervision of a post-doctoral fellow ;
- **Humanoid and Intelligence Systems Lab, Karlsruhe Institute of Technology**: we started a collaboration with Stefanie Speidel and Stefan Suwelack on the topics of real-time soft tissue modeling and laparoscopic augmented reality.
- **SINTEF, Norway**: we are currently collaborating with SINTEF in the context of the European project RASimAs, and also on other aspects, such as the creation of anatomically correct and accurate datasets from patient-specific data. We are also discussing future collaborations in the context of hepatic surgery simulation and augmented reality (we have jointly written a H2020 proposal on this topic).
- **Faculty of Informatics, Masaryk University, Czech Republic**: We began collaborations with Professor Ludek Matyska on biomedical simulations. The PhD thesis of Lukas Rucka on the Validation and verification of soft tissue models; takes place in this context.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Events Selection

8.1.1.1. Chair of Conference Program Committees

- Igor Peterlik was chair in the Workshop on Mathematical and Engineering Methods in Computer Science, October 21 — 23, Telc, Czech Republic
- Nazim Haouchine was a co-chair of the Medical Robotics session at IROS 2016, the International Conference on Intelligent Robots and Systems

8.1.1.2. Reviewer

- Hadrien Courtecuisse made reviews for the IEEE Haptics Symposium and the conference Medical and Biological Engineering and Computing
- Nazim Haouchine made reviews for the International Symposium on Biomedical Imaging

8.1.2. Journal

8.1.2.1. Reviewer - Reviewing Activities

- David Cazier is reviewer for the Computer-Aided Design Journal and for the International Journal of Virtual Reality
- Igor Peterlik is reviewer for the following journals: IEEE Transaction on Haptics, IEEE Transaction on Industrial Electronics, IEEE Transaction on Visualization and Computer Graphics and Computer and Graphics
- Hadrien Courtecuisse is reviewer for the journal Transactions on Haptics and Visual Computer
- Nazim Haouchine made reviews for the International Journal of Computer Assisted Radiology and Surgery

8.1.3. Invited Talks

- Stéphane Cotin gave an invited talk at the 14th International Symposium on Computer Methods in Biomechanics and Biomedical Engineering (Tel Aviv, Israel, 2016)

8.1.4. Scientific Expertise

- Igor Peterlik made scientific expertises at Masaryk University for teaching, supervision of master and Ph.D. students and scientific consultations. Active participation at project funded by Grand Agency of the Czech Republic: *Development of Reliable Methods for Automated Quantitative Characterization of Cell Motility in Fluorescence Microscopy*.

8.1.5. Research Administration

- GTAS : David Cazier heads (with Marc Parenthoen) the national Workgroup on Animation and Simulation of the GDR IG-RV since 2014

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

- Master: Stéphane Cotin, *Medical Imaging (4h)*, M2, Arts et Métiers ParisTech - Paris, France
- Master: Stéphane Cotin, *Medical Imaging (4h)*, M2, Master of Surgical Sciences - Paris, France
- Master: Igor Peterlik, *Modélisation des Systèmes Vivants (10h)*, M2, Master TIC-Santé, Télécom Physique Strasbourg
- Master: Hadrien Courtecuisse, *Real time simulation (30h)*, M2, Master TIC-Santé, Télécom Physique Strasbourg
- Master: Hadrien Courtecuisse, *Real time simulation (10h)*, M1, Master IRMC, Télécom Physique Strasbourg
- Licence: David Cazier, *Web technologies and programming (96h)*, Licence, Université de Strasbourg, France

8.2.2. Supervision

- PhD : Rosalie Plantefeve, *Augmented reality and numerical simulations for resection of hepatic tumors*, Université de Lille, defended on 08/06/2016, supervised by Stéphane Cotin
- PhD in progress: Christoph Paulus, *Modélisation et simulation temps-réel pour la prise en compte des changements topologiques dans les tissus mous*, 01/01/2014, supervised by David Cazier, Stéphane Cotin
- PhD in progress: Jaime Garcia Guevara, *Augmented ultrasound imaging for hepatic surgery*, 01/09/2015, supervised by Stéphane Cotin, Marie-Odile Berger
- PhD in progress: Raffaella Trivisonne, *Computer-aided vascular interventions*, 01/09/2015, Stéphane Cotin, Erwan Kerrien
- PhD in progress: Yinoussa Adagolodjo, *Coupling between robotics and medical simulation for automated procedures*, 01/02/2015, supervised by Hadrien Courtecuisse
- PhD in progress: Fanny Morin, *Non linear simulation for intraoperative guidance for neurosurgery*, 01/10/2014, supervised by Yohan Payan, Matthieu Chabanas, Hadrien Courtecuisse (collaboration with the TIMC laboratory, Grenoble)
- PhD in progress: Lukas Rucka, *Validation and verification of soft tissue models*, 2016 - 2019, supervised by Igor Peterlik and Professor Ludek Matyska in the scope of an international collaboration with Faculty of Informatics, Masaryk University, Czech Republic.
- Master thesis in progress: Petra Ondrejkova, *Contact modeling for forward and inverse simulations of deformable objects in Matlab*, 01/09/2016 - 31/07/2017 , supervised by Igor Peterlik and Prof. Ludek Matyska in the scope of an international collaboration with Faculty of Informatics, Masaryk University, Czech Republic.

8.2.3. Juries

- HdR defense: Benoit Crespin, *Modélisation d'objets complexes, simulation de fluides et interactions*, 14/12/2016, Université de Limoges, David Cazier (reviewer)
- PhD defense: Armelle Bauer, *Modélisation anatomique utilisateur spécifique et animation temps réel : Application a` l'apprentissage de l'anatomie*, 11/11/2016, Université Grenoble, Stéphane Cotin (reviewer)
- PhD defense: Yuen Law, *Real-Time Simulation of B-Mode Ultrasound Images for Medical Training*, 23/11/2016, RWTH Aachen, Germany, Stéphane Cotin (reviewer)
- PhD defense: Lucas Royer, *Real-time Tracking of Deformable Targets in 3D Ultrasound Sequences*, 12/12/2016, INSA Rennes, France, Stéphane Cotin (reviewer)

8.3. Popularization

Stéphane cotin gave invited talks at:

- the Fist European workshop on Nanomedicine, Modeling, Virtual Reality and Robotics applied to surgery (Strasbourg, 2016)
- the Business Engineering and Surgical Technologies symposium (Strasbourg, 2016)
- the OpenYourMind seminar (Paris, 2016)
- IHU Scientific meeting on registration and augmented reality (Strasbourg)

Members of the MIMESIS team contributed to the following events:

- presentation of our research activities during several IHU fellow meetings
- demonstration of our prototype of retina surgery training system during the national congress of ophthalmology (May 2016, Paris)
- demonstration of our prototype of retina surgery training system during the DMLA meeting (September 2016, Paris)
- demonstration of our prototype of retina surgery training system during the regional ophthalmology meeting (November 2016, Strasbourg)

9. Bibliography

Major publications by the team in recent years

[1] H. COURTECUISSE, J. ALLARD, K. PIERRE, S. P.-A. BORDAS, S. COTIN, C. DURIEZ.*Real-time simulation of contact and cutting of heterogeneous soft-tissues*, in "Medical Image Analysis", February 2014, 20, https://hal.inria.fr/hal-01097108.

[2] F. FAURE, C. DURIEZ, H. DELINGETTE, J. ALLARD, B. GILLES, S. MARCHESSEAU, H. TALBOT, H. COURTECUISSE, G. BOUSQUET, I. PETERLIK, S. COTIN.*SOFA: A Multi-Model Framework for Interactive Physical Simulation*, in "Soft Tissue Biomechanical Modeling for Computer Assisted Surgery", Y. PAYAN (editor), Studies in Mechanobiology, Tissue Engineering and Biomaterials, Springer, June 2012, vol. 11, p. 283-321 [*DOI :* 10.1007/8415_2012_125], https://hal.inria.fr/hal-00681539.

[3] N. HAOUCHINE, S. COTIN, I. PETERLIK, J. DEQUIDT, M. SANZ-LOPEZ, E. KERRIEN, M.-O. BERGER.*Impact of Soft Tissue Heterogeneity on Augmented Reality for Liver Surgery*, in "IEEE Transactions on Visualization and Computer Graphics", 2015, vol. 21, n^{o} 5, p. 584 - 597 [*DOI :* 10.1109/TVCG.2014.2377772], https://hal.inria.fr/hal-01136728.

[4] N. HAOUCHINE, J. DEQUIDT, M.-O. BERGER, S. COTIN.*Monocular 3D Reconstruction and Augmentation of Elastic Surfaces with Self-occlusion Handling*, in "IEEE Transactions on Visualization and Computer Graphics", 2015, 14 [*DOI :* 10.1109/TVCG.2015.2452905], https://hal.inria.fr/hal-01186011.

[5] H. TALBOT, N. HAOUCHINE, I. PETERLIK, J. DEQUIDT, C. DURIEZ, H. DELINGETTE, S. COTIN.*Surgery Training, Planning and Guidance Using the SOFA Framework*, in "Eurographics", Zurich, Switzerland, May 2015, https://hal.inria.fr/hal-01160297.

[6] H. TALBOT, F. ROY, S. COTIN.*Augmented Reality for Cryoablation Procedures*, in "SIGGRAPH 2015", Los Angeles, United States, August 2015, https://hal.inria.fr/hal-01180848.

[7] L. UNTEREINER, P. KRAEMER, D. CAZIER, D. BECHMANN.*CPH: a compact representation for hierarchical meshes generated by primal refinement*, in "Computer Graphics Forum", 2015, vol. 34, n^{o} 8, p. 155-166, 5-Year Impact Factor : 1,920 [*DOI :* 10.1111/CGF.12667], https://hal.archives-ouvertes.fr/hal-01162098.

Publications of the year

Doctoral Dissertations and Habilitation Theses

[8] R. PLANTEFÈVE.*Augmented Reality and Numerical Simulations for Hepatic Tumors Resection*, Université Lille 1 Sciences et Technologies, June 2016, https://hal.inria.fr/tel-01338385.

Articles in International Peer-Reviewed Journal

[9] E. KERRIEN, A. YUREIDINI, J. DEQUIDT, C. DURIEZ, R. ANXIONNAT, S. COTIN.*Blood vessel modeling for interactive simulation of interventional neuroradiology procedures*, in "Medical Image Analysis", January 2017, vol. 35, p. 685 - 698 [*DOI :* 10.1016/J.MEDIA.2016.10.003], https://hal.inria.fr/hal-01390923.

[10] S.-H. KONG, N. HAOUCHINE, R. SOARES, A. S. KLYMCHENKO, B. ANDREIUK, B. MARQUES, G. SHABAT, T. PIÉCHAUD, M. DIANA, S. COTIN, J. MARESCAUX.*Robust Augmented Reality registration*

method for Localization of Solid Organs' Tumors Using CT-derived Virtual Biomechanical Model and Fluorescent Fiducials, in "Surgical Endoscopy", 2016, Presented at the SAGES 2016 Annual Meeting, March 16–19, 2016, Boston, MA [*DOI :* 10.1007/s00464-016-5297-8], https://hal.archives-ouvertes.fr/hal-01314963.

[11] C. J. PAULUS, N. HAOUCHINE, S.-H. KONG, R. V. SOARES, D. CAZIER, S. COTIN.*Handling Topological Changes during Elastic Registration: Application to Augmented Reality in Laparoscopic Surgery*, in "International Journal of Computer Assisted Radiology and Surgery (IJCARS)", 2016, https://hal.inria.fr/hal-01397409.

[12] H. TALBOT, F. SPADONI, C. DURIEZ, M. SERMESANT, S. COTIN, H. DELINGETTE.*Interactive Training System for Interventional Electrocardiology Procedures*, in "Lecture notes in computer science", 2016, vol. 8789, p. 11-19 [*DOI :* 10.1007/978-3-319-12057-7_2], https://hal.inria.fr/hal-01338346.

International Conferences with Proceedings

[13] Y. ADAGOLODJO, L. GOFFIN, M. DE MATHELIN, H. COURTECUISSE.*Inverse real-time Finite Element simulation for robotic control of flexible needle insertion in deformable tissues*, in "IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2016)", Daejeon, South Korea, October 2016, https://hal.archives-ouvertes.fr/hal-01353925.

[14] N. HAOUCHINE, M.-O. BERGER, S. COTIN.*Simultaneous Pose Estimation and Augmentation of Elastic Surfaces from a Moving Monocular Camera*, in "International Symposium on Mixed and Augmented Reality", Merida, Mexico, September 2016, https://hal.inria.fr/hal-01353189.

[15] N. HAOUCHINE, S. COTIN.*Segmentation and Labelling of Intra-operative Laparoscopic Images using Structure from Point Cloud*, in "International Symposium on Biomedical Imaging : "From Nano to Macro" (ISBI 2016)", Prague, Czech Republic, April 2016, https://hal.archives-ouvertes.fr/hal-01314970.

[16] N. HAOUCHINE, F. ROY, L. UNTEREINER, S. COTIN.*Using Contours as Boundary Conditions for Elastic Registration during Minimally Invasive Hepatic Surgery*, in "International Conference on Intelligent Robots and Systems", Daejeon, South Korea, October 2016, https://hal.inria.fr/hal-01353185.

Conferences without Proceedings

[17] F. MORIN, I. REINERTSEN, H. COURTECUISSE, O. PALOMBI, B. MUNKVOLD, H. K. BØ, Y. PAYAN, M. CHABANAS.*Vessel-based brain-shift compensation using elastic registration driven by a patient-specific finite element model*, in "International Conference on Information Processing in Computer-Assisted Interventions (IPCAI)", Heidelberg, Germany, June 2016, https://hal.archives-ouvertes.fr/hal-01331713.

[18] R. TRIVISONNE, I. PETERLIK, S. COTIN, H. COURTECUISSE.*3D Physics-Based Registration of 2D Dynamic MRI Data*, in "MMVR - Medicine Meets Virtual Reality", Los Angeles, United States, April 2016, https://hal.inria.fr/hal-01254388.

References in notes

[19] H. COURTECUISSE, J. ALLARD, K. PIERRE, S. P.-A. BORDAS, S. COTIN, C. DURIEZ.*Real-time simulation of contact and cutting of heterogeneous soft-tissues*, in "Medical Image Analysis", February 2014, 20, https://hal.inria.fr/hal-01097108.

[20] F. DERVAUX, I. PETERLIK, J. DEQUIDT, S. COTIN, C. DURIEZ.*Haptic Rendering of Interacting Dynamic Deformable Objects Simulated in Real-Time at Different Frequencies*, in "IROS - IEEE/RSJ International Conference on Intelligent Robots and Systems", Tokyo, Japan, IEEE, November 2013, https://hal.inria.fr/hal-00842866.

[21] N. HAOUCHINE, J. DEQUIDT, M.-O. BERGER, S. COTIN.*Single View Augmentation of 3D Elastic Objects*, in "International Symposium on Mixed and Augmented Reality - ISMAR", Munich, Germany, September 2014, https://hal.inria.fr/hal-01056323.

[22] N. HAOUCHINE, J. DEQUIDT, E. KERRIEN, M.-O. BERGER, S. COTIN.*Physics-based Augmented Reality for 3D Deformable Object*, in "Eurographics Workshop on Virtual Reality Interaction and Physical Simulation", Darmstadt, Germany, December 2012, https://hal.inria.fr/hal-00768362.

[23] I. PETERLIK, H. COURTECUISSE, C. DURIEZ, S. COTIN.*Model-Based Identification of Anatomical Boundary Conditions in Living Tissues*, in "Information Processing in Computer Assisted Interventions", Fukuoka, Japan, June 2014 [*DOI :* 10.1007/978-3-319-07521-1_21], https://hal.inria.fr/hal-01264434.

[24] I. PETERLIK, M. NOUICER, C. DURIEZ, S. COTIN, A. KHEDDAR.*Constraint-based haptic rendering of multirate compliant mechanisms*, in "IEEE Transactions on Haptics (ToH)", June 2011, vol. 4, n^{o} 3, p. 175-187 [*DOI :* 10.1109/TOH.2011.41], https://hal-lirmm.ccsd.cnrs.fr/lirmm-00784081.

[25] T. PITIOT, D. CAZIER, T. JUND, A. HABIBI, P. KRAEMER.*Deformable polygonal agents in crowd simulation*, in "Computer Animation and Virtual Worlds", 2014, vol. 25, n^{o} 3-4, p. 341–350.

[26] R. PLANTEFÈVE, I. PETERLIK, N. HAOUCHINE, S. COTIN.*Patient-specific Biomechanical Modeling for Guidance during Minimally-invasive Hepatic Surgery*, in "Annals of Biomedical Engineering", August 2015, https://hal.inria.fr/hal-01205194.

[27] L. UNTEREINER, D. CAZIER, D. BECHMANN.*n-Dimensional multiresolution representation of subdivision meshes with arbitrary topology*, in "Graphical Models", 2013, vol. 75, n^{o} 5, p. 231–246.

[28] G. ZAVARISE, P. WRIGGERS.*Trends in Computational Contact Mechanics*, Lecture Notes in Applied and Computational Mechanics, Springer Berlin Heidelberg, 2011, https://books.google.fr/books?id=faSoa3k6NCYC.

Project-Team MULTISPEECH

Speech Modeling for Facilitating Oral-Based Communication

IN COLLABORATION WITH: Laboratoire lorrain de recherche en informatique et ses applications (LORIA)

IN PARTNERSHIP WITH:
CNRS

Université de Lorraine

RESEARCH CENTER
Nancy - Grand Est

THEME
Language, Speech and Audio

Table of contents

Project-Team MULTISPEECH

Creation of the Team: 2014 July 01, updated into Project-Team: 2015 July 01

Keywords:

Computer Science and Digital Science:

3.1.4. - Uncertain data
3.4.6. - Neural networks
3.4.8. - Deep learning
5.1.7. - Multimodal interfaces
5.7.2. - Music
5.7.3. - Speech
5.7.4. - Analysis
5.7.5. - Synthesis
5.8. - Natural language processing
5.9.1. - Sampling, acquisition
5.9.2. - Estimation, modeling
5.9.3. - Reconstruction, enhancement
5.9.5. - Sparsity-aware processing
5.10.2. - Perception
5.11.2. - Home/building control and interaction
6.2.4. - Statistical methods
6.3.1. - Inverse problems
6.3.5. - Uncertainty Quantification
8.2. - Machine learning
8.3. - Signal analysis

Other Research Topics and Application Domains:

4.3.3. - Wind energy
8.1.2. - Sensor networks for smart buildings
8.4. - Security and personal assistance
9.1.1. - E-learning, MOOC
9.2.1. - Music, sound
9.2.2. - Cinema, Television
9.4.1. - Computer science
9.4.2. - Mathematics
9.4.5. - Data science
9.5.8. - Linguistics
9.5.10. - Digital humanities

1. Members

Research Scientists

Denis Jouvet [Team leader, Inria, Senior Researcher, HDR]

Anne Bonneau [CNRS, Researcher]
Dominique Fohr [CNRS, Researcher]
Yves Laprie [CNRS, Senior Researcher, HDR]
Antoine Liutkus [Inria, Researcher]
Emmanuel Vincent [Inria, Senior Researcher, HDR]

Faculty Members

Vincent Colotte [Univ. Lorraine, Associate Professor]
Irène Illina [Univ. Lorraine, Associate Professor, HDR]
Odile Mella [Univ. Lorraine, Associate Professor]
Slim Ouni [Univ. Lorraine, Associate Professor, HDR]
Agnès Piquard-Kipffer [ESPE, Univ. Lorraine, Associate Professor]
Romain Serizel [Univ. Lorraine, Associate Professor, from Sep 2016]

Technical Staff

Ismaël Bada [CNRS, from Aug 2016]
Sara Dahmani [Inria]
Valérian Girard [Univ. Lorraine, until Jun 2016; then CNRS]
Karan Nathwani [Inria, from Jun 2016]
Aghilas Sini [CNRS, until Nov 2016]
Sunit Sivasankaran [Inria]

PhD Students

Ken Deguernel [Inria]
Baldwin Dumortier [Inria]
Mathieu Fontaine [Inria, from May 2016]
Amal Houidhek [École Nationale d'Ingénieurs de Tunis, Tunisie]
Yang Liu [Univ. Lorraine, from Oct 2016]
Aditya Nugraha [Inria]
Luiza Orosanu [Inria, until Feb 2016]
Imran Sheikh [Univ. Lorraine]
Anastasiia Tsukanova [Univ. Lorraine, from May 2016]
Imene Zangar [École Nationale d'Ingénieurs de Tunis, Tunisie]

Post-Doctoral Fellows

Mohamed Bouallegue [Univ. Lorraine, until Sep 2016]
Benjamin Elie [CNRS]
Sucheta Ghosh [CNRS]
Juan Andres Morales Cordovilla [Inria, until Mar 2016]

Visiting Scientists

Sebastian Gonzalez Mora [Univ. Chile, Jan 2016]
Benjamin Martinez Elizalde [Carnegie Mellon University, from May 2016 until Aug 2016]
Dayana Ribas [CENATAV, from Sep 2016 until Dec 2016]
Ziteng Wang [Institute of Acoustics, Chinese Academy of Sciences, from Sep 2016]

Administrative Assistants

Antoinette Courrier [CNRS]
Sylvie Musilli [Univ. Lorraine]
Hélène Zganic [Inria]

Others

Lucas Antonelli [Inria, Intern, from Apr 2016 until Jun 2016]
Imen Ben Othmane [ESTI, Univ. de Carthage, Tunisia, Visiting PhD Student, until Jun 2016]
Clement Bordes [Inria, Intern, from Jun 2016 until Sep 2016]
Freha Boumazza [Uuiv. Hassiba Benbouali de Chlef, Algérie, Visiting PhD Student, Mar 2016]
Anna Currey [Univ. Lorraine, Intern, from Feb 2016 until Jun 2016]

Siddharth Dalmia [Univ. Lorraine, Intern, until Jul 2016]
Narjes Daoud [ESTI, Univ. de Carthage, Tunisia, Intern, from Mar 2016 until Aug 2016]
Boyuan Deng [Univ. Lorraine, Intern, from Feb 2016 until Jul 2016]
Diego Di Carlo [Inria, Intern, from Nov 2016]
Bertrand Muller [Inria, Intern, from Apr 2016 until Jun 2016]

2. Overall Objectives

2.1. Overall Objectives

MULTISPEECH is a joint project between Inria, CNRS and University of Lorraine, hosted in the LORIA laboratory (UMR 7503). The goal of the project is the modeling of speech for facilitating oral-based communication. The name MULTISPEECH comes from the following aspects that are particularly considered:

- **Multisource aspects** - which means dealing with speech signals originating from several sources, such as speaker plus noise, or overlapping speech signals resulting from multiple speakers; sounds captured from several microphones are also considered.
- **Multilingual aspects** - which means dealing with speech in a multilingual context, as for example for computer assisted language learning, where the pronunciations of words in a foreign language (i.e., non-native speech) is strongly influenced by the mother tongue.
- **Multimodal aspects** - which means considering simultaneously the various modalities of speech signals, acoustic and visual, in particular for the expressive synthesis of audio-visual speech.

The project is organized along the three following scientific challenges:

- **The explicit modeling of speech.** - Speech signals result from the movements of articulators. A good knowledge of their position with respect to sounds is essential to improve, on the one hand, articulatory speech synthesis, and on the other hand, the relevance of the diagnosis and of the associated feedback in computer assisted language learning. Production and perception processes are interrelated, so a better understanding of how humans perceive speech will lead to more relevant diagnoses in language learning as well as pointing out critical parameters for expressive speech synthesis. Also, as the expressivity translates into both visual and acoustic effects that must be considered simultaneously, the multimodal components of expressivity, which are both on the voice and on the face, will be addressed to produce expressive multimodal speech.
- **The statistical modeling of speech.** - Statistical approaches are common for processing speech and they achieve performance that makes possible their use in actual applications. However, speech recognition systems still have limited capabilities (for example, even if large, the vocabulary is limited) and their performance drops significantly when dealing with degraded speech, such as noisy signals, distant microphone recording and spontaneous speech. Source separation based approaches are investigated as a way of making speech recognition systems more robust to noise. Handling new proper names is an example of critical aspect that is tackled, along with the use of statistical models for speech-text automatic alignment and for speech production.
- **The estimation and the exploitation of uncertainty in speech processing.** - Speech signals are highly variable and often disturbed with noise or other spurious signals (such as music or undesired extra speech). In addition, the output of speech enhancement and of source separation techniques is not exactly the accurate "clean" original signal, and estimation errors have to be taken into account in further processing. This is the goal of computing and handling the uncertainty of the reconstructed signal provided by source separation approaches. Finally, MULTISPEECH also aims at estimating the reliability of phonetic segment boundaries and prosodic parameters for which no such information is yet available.

Although being interdependent, each of these three scientific challenges constitutes a founding research direction for the MULTISPEECH project. Consequently, the research program is organized along three research directions, each one matching a scientific challenge. A large part of the research is conducted on French speech data; English and German languages are also considered in speech recognition experiments and language learning. Adaptation to other languages of the machine learning based approaches is possible, depending on the availability of corresponding speech corpora.

3. Research Program

3.1. Explicit Modeling of Speech Production and Perception

Speech signals are the consequence of the deformation of the vocal tract under the effect of the movements of the articulators (jaw, lips, tongue, ...) to modulate the excitation signal produced by the vocal cords or air turbulence. These deformations are visible on the face (lips, cheeks, jaw) through the coordination of different orofacial muscles and skin deformation induced by the latter. These deformations may also express different emotions. We should note that human speech expresses more than just phonetic content, to be able to communicate effectively. In this project, we address the different aspects related to speech production from the modeling of the vocal tract up to the production of expressive audiovisual speech. Phonetic contrasts used by the phonological system of any language result from constraints imposed by the nature of the human speech production apparatus. For a given language these contrasts are organized so as to guarantee that human listeners can identify (categorize) sounds robustly. The study of the categorization of sounds and prosody thus provides a complementary view on speech signals by focusing on the discrimination of sounds by humans, particularly in the context of language learning.

3.1.1. Articulatory modeling

Modeling speech production is a major issue in speech sciences. Acoustic simulation makes the link between articulatory and acoustic domains. Unfortunately this link cannot be fully exploited because there is almost always an acoustic mismatch between natural and synthetic speech generated with an articulatory model approximating the vocal tract. However, the respective effects of the geometric approximation, of the fact of neglecting some cavities in the simulation, of the imprecision of some physical constants and of the dimensionality of the acoustic simulation are still unknown. Hence, the first objective is to investigate the origin of the acoustic mismatch by designing more precise articulatory models, developing new methods to acquire tridimensional Magnetic Resonance Imaging (MRI) data of the entire vocal tract together with denoised speech signals, and evaluating several approaches of acoustic simulation. The articulatory data acquisition relies on a head-neck antenna at Nancy Hospital to acquire MRI of the vocal tract, and on the articulograph Carstens AG501 available in the laboratory.

Up to now, acoustic-to-articulatory inversion has been addressed as an instantaneous problem, articulatory gestures being recovered by concatenating local solutions. The second objective is thus to investigate how more elaborated strategies (a syllabus of primitive gestures, articulatory targets…) can be incorporated in the acoustic-to-articulatory inversion algorithms to take into account dynamic aspects.

3.1.2. Expressive acoustic-visual synthesis

Speech is considered as a bimodal communication means; the first modality is audio, provided by acoustic speech signals and the second one is visual, provided by the face of the speaker. In our approach, the Acoustic-Visual Text-To-Speech synthesis (AV-TTS) is performed simultaneously with respect to its acoustic and visible components, by considering a bimodal signal comprising both acoustic and visual channels. A first AV-TTS system has been developed resulting in a talking head; the system relied on 3D-visual data and on an extension of our acoustic-unit concatenation text-to-speech synthesis system (SoJA). An important goal is to provide an audiovisual synthesis that is intelligible, both acoustically and visually. Thus, we continue working on adding visible components of the head through a tongue model and a lip model. We will also improve the TTS engine to increase the accuracy of the unit selection simultaneously into the acoustic and visual domains. To acquire the facial data, we consider using a marker-less motion capture system using a kinect-like system with a face tracking software, which constitutes a relatively low-cost alternative to the Vicon system.

Another challenging research goal is to add expressivity in the AV-TTS. The expressivity comes through the acoustic signal (prosody aspects) and also through head and eyebrow movements. One objective is to add a prosodic component in the TTS engine in order to take into account some prosodic entities such as emphasis (to highlight some important key words). One intended approach will be to explore an expressivity measure at sound, syllable and/or sentence levels that describes the degree of perception or realization of an expression/emotion (audio and 3D domain). Such measures will be used as criteria in the selection process of the synthesis system. To tackle the expressivity issue we will also investigate Hidden Markov Model (HMM) based synthesis which allows for easy adaptation of the system to available data and to various conditions.

3.1.3. Categorization of sounds and prosody for native and non-native speech

Discriminating speech sounds and prosodic patterns is the keystone of language learning whether in the mother tongue or in a second language. This issue is associated with the emergence of phonetic categories, i.e., classes of sounds related to phonemes and prosodic patterns. The study of categorization is concerned not only with acoustic modeling but also with speech perception and phonology. Foreign language learning raises the issue of categorizing phonemes of the second language given the phonetic categories of the mother tongue. Thus, studies on the emergence of new categories, whether in the mother tongue (for people with language deficiencies) or in a second language, must rely upon studies on native and non-native acoustic realizations of speech sounds and prosody, and on perceptual experiments. Concerning prosody, studies are focused on native and non-native realizations of modalities (e.g., question, affirmation, command, ...), as well as non-native realizations of lexical accents and focus (emphasis).

For language learning, the analysis of the prosody and of the acoustic realization of the sounds aims at providing automatic feedback to language learners with respect to acquisition of prosody as well as acquisition of a correct pronunciation of the sounds of the foreign language. Concerning the mother tongue we are interested in the monitoring of the process of sound categorization in the long term (mainly at primary school) and its relation with the learning of reading and writing skills [7], especially for children with language deficiencies.

3.2. Statistical Modeling of Speech

Whereas the first research direction deals with the physical aspects of speech and its explicit modeling, this second research direction investigates statistical models for speech data. Acoustic models are used to represent the pronunciation of the sounds or other acoustic events such as noise. Whether they are used for source separation, for speech recognition, for speech transcription, or for speech synthesis, the achieved performance strongly depends on the accuracy of these models. At the linguistic level, MULTISPEECH investigates models for handling the context (beyond the few preceding words currently handled by the n-gram models) and evolutive lexicons necessary when dealing with diachronic audio documents. Statistical approaches are also useful for generating speech signals. Along this direction, MULTISPEECH considers voice transformation techniques, with their application to pathological voices, and statistical speech synthesis applied to expressive multimodal speech synthesis.

3.2.1. Source separation

Acoustic modeling is a key issue for automatic speech recognition. Despite the progress made for many years, current speech recognition applications rely on strong constraints (close-talk microphone, limited vocabulary, or restricted syntax) to achieve acceptable performance. The quality of the input speech signals is particularly important and performance degrades quickly with noisy signals. Accurate signal enhancement techniques are therefore essential to increase the robustness of both automatic speech recognition and speech-text alignment systems to noise and non-speech events.

In MULTISPEECH, focus is set on source separation techniques using multiple microphones and/or models of non-speech events. Some of the challenges include getting the most of the new modeling frameworks based on alpha-stable distributions and deep neural networks, combining them with established spatial filtering approaches, modeling more complex properties of speech and audio sources (phase, inter-frame and inter-frequency properties), and exploiting large data sets of speech, noise, and acoustic impulse responses to automatically discover new models. Beyond the definition of such models, the difficulty will be to design scalable estimation algorithms robust to overfitting, integrate them into the recently developed FASST [6] and KAM software frameworks if relevant, and develop new software frameworks otherwise.

3.2.2. Linguistic modeling

MULTISPEECH investigates lexical and language models in speech recognition with a focus on improving the processing of proper names and of spontaneous speech. Proper names are relevant keys in information indexing, but are a real problem in transcribing many diachronic spoken documents which refer to data, especially proper names, that evolve over time. This leads to the challenge of dynamically adjusting lexicons and language models through the use of the context of the documents or of some relevant external information. We also investigate language models defined on a continuous space (through neural network based approaches) in order to achieve a better generalization on unseen data, and to model long-term dependencies. We also want to introduce into these models additional relevant information such as linguistic features, semantic relation, topic or user-dependent information.

Other topics are spontaneous speech and pronunciation lexicons. Spontaneous speech utterances are often ill-formed and frequently contain disfluencies (hesitations, repetitions, ...) that degrade speech recognition performance. Hence the objective of improving the modeling of disfluencies and of spontaneous speech pronunciation variants. Attention will also be set on pronunciation lexicons with respect to non-native speech and foreign names. Non-native pronunciation variants have to take into account frequent mis-pronunciations due to differences between mother tongue and target language phoneme inventories. Proper name pronunciation variants are a similar problem where difficulties are mainly observed for names of foreign origin that can be pronounced either in a French way or kept close to foreign origin native pronunciation.

3.2.3. Speech generation by statistical methods

Over the last few years statistical speech synthesis has emerged as an alternative to corpus-based speech synthesis. The announced advantages of the statistical speech synthesis are the possibility to deal with small amounts of speech resources and the flexibility for adapting models (for new emotions or new speakers), however, the quality is not as good as that of the concatenation-based speech synthesis. MULTISPEECH will focus on a hybrid approach, combining corpus-based synthesis, for its high-quality speech signal output, and HMM-based speech synthesis for its flexibility to drive selection, and the main challenge will be on its application to producing expressive audio-visual speech.

Moreover, in the context of acoustic feedback in foreign language learning, voice modification approaches are investigated to modify the learner's (or teacher's) voice in order to emphasize the difference between the learner's acoustic realization and the expected realization.

3.3. Uncertainty Estimation and Exploitation in Speech Processing

This axis focuses on the uncertainty associated with some processing steps. Uncertainty stems from the high variability of speech signals and from imperfect models. For example, enhanced speech signals resulting from source separation are not exactly the clean original speech signals. Words or phonemes resulting from automatic speech recognition contain errors, and the phone boundaries resulting from an automatic speech-text alignment are not always correct, especially in acoustically degraded conditions. Hence it is important to know the reliability of the results and/or to estimate the uncertainty of the results.

3.3.1. Uncertainty and acoustic modeling

Because small distortions in the separated source signals can translate into large distortions in the cepstral features used for speech recognition, this limits the recognition performance on noisy data. One way to address this issue is to estimate the uncertainty of the separated sources in the form of their posterior distribution and to propagate this distribution, instead of a point estimate, through the subsequent feature extraction and speech decoding stages. Although major improvements have been demonstrated in proof-of-concept experiments using knowledge of the true uncertainty, accurate uncertainty estimation and propagation remains an open issue.

MULTISPEECH seeks to provide more accurate estimates of the posterior distribution of the separated source signals accounting for, e.g., posterior correlations over time and frequency which have not been considered so far. The framework of variational Bayesian (VB) inference appears to be a promising direction. Mappings learned on training data and fusion of multiple uncertainty estimators are also explored. The estimated uncertainties are then exploited for acoustic modeling in speech recognition and, in the future, also for speech-text alignment. This approach may later be extended to the estimation of the resulting uncertainty of the acoustic model parameters and of the acoustic scores themselves.

3.3.2. Uncertainty and phonetic segmentation

The accuracy of the phonetic segmentation is important in several cases, as for example for the computation of prosodic features, for avoiding incorrect feedback to the learner in computer assisted foreign language learning, or for the post-synchronization of speech with face/lip images. Currently the phonetic boundaries obtained are quite correct on good quality speech, but the precision degrades significantly on noisy and non-native speech. Phonetic segmentation aspects will be investigated, both in speech recognition (i.e., spoken text unknown) and in forced alignment (i.e., when the spoken text is known).

In the same way that combining several speech recognition outputs leads to improved speech recognition performance, MULTISPEECH will investigate the combination of several speech-text alignments as a way of improving the quality of speech-text alignment and of determining which phonetic boundaries are reliable and which ones are not, and also for estimating the uncertainty of the boundaries. Knowing the reliability of the boundaries will also be useful when segmenting speech corpora; this will help deciding which parts of the corpora need to be manually checked and corrected without an exhaustive checking of the whole corpus.

3.3.3. Uncertainty and prosody

Prosody information is also investigated as a means for structuring speech data (determining sentence boundaries, punctuation. . .) possibly in addition to syntactic dependencies. Structuring automatic transcription output is important for further exploitation of the transcription results such as easier reading after the addition of punctuation, or exploitation of full sentences in automatic translation. Prosody information is also necessary for determining the modality of the utterance (question or not), as well as determining accented words.

Prosody information comes from the fundamental frequency, the duration of the sounds and their energy. Any error in estimating these parameters may lead to a wrong decision. MULTISPEECH will investigate estimating the uncertainty of the duration of the phones (see uncertainty of phonetic boundaries above) and on the fundamental frequency, as well as how this uncertainty shall be propagated in the detection of prosodic phenomena such as accented words, utterance modality, or determination of the structure of the utterance.

4. Application Domains

4.1. Introduction

Approaches and models developed in the MULTISPEECH project are intended to be used for facilitating oral communication in various situations through enhancements of the communication channels, either directly via automatic speech recognition or speech production technologies, or indirectly, thanks to computer assisted language learning. Applications also include the usage of speech technologies for helping people in handicapped situations or for improving their autonomy. Foreseen application domains are related to computer assisted learning, health and autonomy (more precisely aided communication and monitoring), annotation and processing of spoken documents, and multimodal computer interaction.

4.2. Computer Assisted Learning

Although speaking seems quite natural, learning foreign languages, or learning the mother tongue for people with language deficiencies, represents critical cognitive stages. Hence, many scientific activities have been devoted to these issues either from a production or a perception point of view. The general guiding principle with respect to computer assisted mother or foreign language learning is to combine modalities or to augment speech to make learning easier. Based upon a comparison of the learner's production to a reference, automatic diagnoses of the learner's production can be considered, as well as perceptual feedback relying on an automatic transformation of the learner's voice. The diagnosis step strongly relies on the studies on categorization of sounds and prosody in the mother tongue and in the second language. Furthermore, reliable diagnosis on each individual utterance is still a challenge, and elaboration of advanced automatic feedback requires a temporally accurate segmentation of speech utterances into phones and this explains why accurate segmentation of native and non-native speech is an important topic in the field of acoustic speech modeling.

4.3. Aided Communication and Monitoring

A foreseen application aims at improving the autonomy of elderly or disabled people, and fit with smartroom applications. In a first step, source separation techniques could be tuned and should help for locating and monitoring people through the detection of sound events inside apartments. In a longer perspective, adapting speech recognition technologies to the voice of elderly people should also be useful for such applications, but this requires the recording of adequate databases. Sound monitoring in other application fields (security, environmental monitoring) could also be envisaged.

4.4. Annotation and Processing of Spoken Documents and Audio Archives

A first type of annotation consists in transcribing a spoken document in order to get the corresponding sequences of words, with possibly some complementary information, such as the structure (punctuation) or the modality (affirmation/question) of the utterances to make the reading and understanding easier. Typical applications of the automatic transcription of radio or TV shows, or of any other spoken document, include making possible their access by deaf people, as well as by text-based indexing tools.

A second type of annotation is related to speech-text alignment, which aims at determining the starting and ending times of the words, and possibly of the sounds (phonemes). This is of interest in several cases as for example, for annotating speech corpora for linguistic studies, and for synchronizing lip movements with speech sounds, for example for avatar-based communications. Although good results are currently achieved on clean data, automatic speech-text alignment needs to be improved for properly processing noisy spontaneous speech data and needs to be extended to handle overlapping speech.

Large audio archives are important for some communities of users, e.g., linguists, ethnologists or researchers in digital humanities in general. In France, a notorious example is the "Archives du CNRS — Musée de l'homme", gathering about 50,000 recordings dating back to the early 1900s. When dealing with very old recordings, the practitioner is often faced with the problem of noise. This stems from the fact that a lot of interesting material from a scientific point of view is very old or has been recorded in very adverse noisy conditions, so that the resulting audio is poor. The work on source separation can lead to the design of semi-automatic denoising and enhancement features, that would allow these researchers to significantly enhance their investigation capabilities, even without expert knowledge in sound engineering.

Finally, there is also a need for speech signal processing techniques in the field of multimedia content creation and rendering. Relevant techniques include speech and music separation, speech equalization, prosody modification, and speaker conversion.

4.5. Multimodal Computer Interactions

Speech synthesis has tremendous applications in facilitating communication in a human-machine interaction context to make machines more accessible. For example, it started to be widely common to use acoustic speech synthesis in smartphones to make possible the uttering of all the information. This is valuable in particular in the case of handicap, as for blind people. Audiovisual speech synthesis, when used in an application such as a talking head, i.e., virtual 3D animated face synchronized with acoustic speech, is beneficial in particular for hard-of-hearing individuals. This requires an audiovisual synthesis that is intelligible, both acoustically and visually. A talking head could be an intermediate between two persons communicating remotely when their video information is not available, and can also be used in language learning applications as vocabulary tutoring or pronunciation training tool. Expressive acoustic synthesis is of interest for the reading of a story, such as audiobook, to facilitate the access to literature (for instance for blind people or illiterate people).

5. Highlights of the Year

5.1. Highlights of the Year

We ranked 1st ex aqueo for the ”Professionally produced music recordings” task of the 2016 Signal Separation Evaluation Campaign (SiSEC) [39].

6. New Software and Platforms

6.1. ASTALI

Automatic Speech-Text Alignment Software
KEYWORD: Speech-text alignment
FUNCTIONAL DESCRIPTION

ASTALI is a software for aligning a speech signal with its corresponding orthographic transcription (given in simple text file for short audio signals or in .trs files as generated by transcriber for longer speech signals). Using a phonetic lexicon and automatic grapheme-to-phoneme converters, all the possible sequences of phones corresponding to the text are generated. Then, using acoustic models, the tool finds the best phone sequence and provides the boundaries at the phone and at the word levels. ASTALI is available through a web application, which makes the service easy to use, without requiring any software downloading. This year, the integration of the web application on the ORTOLANG platform has been finalized.

- Participants: Dominique Fohr, Odile Mella, Antoine Chemardin, Valérian Girard and Denis Jouvet
- Contact: Dominique Fohr
- URLs: https://www.ortolang.fr/market/tools/astali; http://astali.loria.fr/; and http://ortolang108.inist.fr/astali/

6.2. dnnsep

Multichannel audio source separation with deep neural networks
KEYWORDS: Audio - Source Separation - Deep learning
SCIENTIFIC DESCRIPTION

dnnsep is the only source separation software relying on multichannel Wiener filtering based on deep learning. Deep neural networks are used to initialize and reestimate the power spectrum of the sources at every iteration of an expectation-maximization (EM) algorithm. This results in state-of-the-art separation quality for both speech and music.
FUNCTIONAL DESCRIPTION

dnnsep is a new software that combines deep neural networks and multichannel signal processing for speech enhancement and separation of musical recordings.

- Participants: Aditya Nugraha, Antoine Liutkus and Emmanuel Vincent
- Contact: Emmanuel Vincent

6.3. JSnoori

FUNCTIONAL DESCRIPTION

JSnoori is written in Java and uses signal processing algorithms developed within the WinSnoori software with the double objective of being a platform independent signal visualization and manipulation tool, and also for designing exercises for learning the prosody of a foreign language. JSnoori can be used directly or via scripts written in Jython. This year, several approaches for computing the fundamental frequency have been added; and, JSnoori is now available through the ORTOLANG platform.

- Participants: Yves Laprie, Slim Ouni, Aghilas Sini and Ilef Ben Farhat
- Contact: Yves Laprie

6.4. KATS

Kaldi-based Automatic Transcription System
KEYWORD: Speech recognition
FUNCTIONAL DESCRIPTION

KATS is a multipass system for transcribing audio data, and in particular radio or TV shows. The audio stream is first split into homogeneous segments that are decoded using the most adequate acoustic model with a large vocabulary continuous speech recognition engine. In this new software, the recognition engine is based on the Kaldi toolkit, and uses Deep Neural Network - DNN - based acoustic models. An extra processing pass is run in order to rescore the n-best hypotheses with a higher order language model.

- Participants: Odile Mella, Dominique Fohr and Denis Jouvet
- Contact: Dominique Fohr
- URL: Available online on the A||go platform: https://allgo.inria.fr/app/loriasts_kaldi

6.5. PLAVIS

Sofware for audio-visual and multimodal data acquisition and processing
FUNCTIONAL DESCRIPTION

Within the ADT PLAVIS (cf. 9.2.12), we have developed a software for 3D audiovisual data acquisition and synthesis. The system incorporates an animation module of the talking head to reconstruct the animated face along with audio. The acquisition software handles one or several acquisition systems: motion-capture (Kinect-like), Vicon or EMA systems. The various acquisition channels are synchronized. The animation technique can exploit multimodal data to define blendshapes that controls the face; the advantage of using blendshapes is to be able to transfer the animation from one 3D human model to another. A semi-automatic acoustic boundary correction process is integrated in the corpus building process. The text-to-speech processing is driven by the Soja software.

- Participants: Vincent Colotte, Slim Ouni, Sara Dahmani
- Contact: Vincent Colotte

6.6. SOJA

Speech Synthesis platform in JAva
FUNCTIONAL DESCRIPTION

SOJA is a software for Text-To-Speech synthesis (TTS) which relies on a non uniform unit selection algorithm. It performs all steps from text input to speech signal output. A set of associated tools is available for elaborating a corpus for a TTS system (transcription, alignment. . .). Currently, the corpus contains about 3 hours of speech recorded by a female speaker. Most of the modules are in Java, some are in C. The SOJA software runs under Windows and Linux. It can be launched with a graphical user interface or directly integrated in a Java code or by following the client-server paradigm. During 2016, the part of code in C was reduced to go to a full-Java software in the future. The natural language processing can now be restarted from any step. This functionality is useful for instance during corpus processing when using semi-automatic boundaries correction.

- Participants: Vincent Colotte and Alexandre Lafosse
- Contact: Vincent Colotte

6.7. VisArtico

Visualization of EMA Articulatory data
FUNCTIONAL DESCRIPTION

VisArtico is a user-friendly software which allows visualizing EMA data acquired by an articulograph (AG500, AG501 or NDI Wave). This visualization software has been designed so that it can directly use the data provided by the articulograph to display the articulatory coil trajectories, synchronized with the corresponding acoustic recordings. Moreover, VisArtico not only allows viewing the coil trajectories but also enriches the visual information by indicating clearly and graphically the data for the tongue, lips and jaw. In addition, it is possible to insert images (MRI or X-Ray, for instance) to compare the EMA data with data obtained through other acquisition techniques. It is possible to generate a movie for any articulatory-acoustic sequence. During 2016, we have made a new version of VisArtico where the 3D view is now based on OpenGL. This allows a better quality rendering. It is possible to make measurement between sensors to compute the distance. Finally, we added the possibility to display the fundamental frequency on the spectrogram.

- Participants: Slim Ouni, Loic Mangeonjean, Ilef Ben Farhat and Bertrand Muller
- Contact: Slim Ouni
- URL: http://visartico.loria.fr

6.8. Xarticulators

KEYWORD: Medical imaging
FUNCTIONAL DESCRIPTION

The Xarticulators software is intended to delineate contours of speech articulators in X-ray images, construct articulatory models and synthesize speech from X-ray films. This software provides tools to track contours automatically, semi-automatically or by hand, to make the visibility of contours easier, to add anatomical landmarks to speech articulators and to synchronize images with the sound. In addition we also added the possibility of processing digitized manual delineation results made on sheets of papers when no software is available. Xarticulators also enables the construction of adaptable linear articulatory models from the X-ray images and incorporates acoustic simulation tools to synthesize speech signals from the vocal tract shape. Recent work was on the possibility of synthesizing speech from X-ray or 2D-MRI films.
During 2016, we developed a new version of the articulatory model which incorporates a more realistic model of the epiglottis and lips.

- Contact: Yves Laprie

6.9. Platforms

6.9.1. Platform MultiMod : Multimodal Acquisition Data Platform

FUNCTIONAL DESCRIPTION

Within a LORIA exploratory project (cf. 9.2.13), we have set up an acquisition hardware platform to acquire multimodal data in speech communication context. The system is composed of the articulograph Carstens AG501 (which was acquired as part of the EQUIPEX ORTOLANG - cf. 9.2.1), 4 Vicon cameras (a motion capture system), an Intel RealSense which is a depth camera (acquired as part of the project COREXp - cf. 9.1.1), a video camera and a microphone. With such heterogeneous hardware the synchronization is essential; this is achieved through a trigger device. All the data processing is performed with the PLAVIS software. This year, the system has been used to acquire multimodal data for the MCC project (cf. 9.4.2.1) and a first exploratory expressive multimodal corpus [40].

- Participants: Slim Ouni, Vincent Colotte, Valerian Girard, Sara Dahmani
- Contact: Slim Ouni

7. New Results

7.1. Explicit Modeling of Speech Production and Perception

Participants: Yves Laprie, Slim Ouni, Vincent Colotte, Anne Bonneau, Agnès Piquard-Kipffer, Denis Jouvet, Odile Mella, Dominique Fohr, Benjamin Elie, Sucheta Ghosh, Anastasiia Tsukanova, Yang Liu, Sara Dahmani, Valérian Girard, Aghilas Sini.

7.1.1. Articulatory modeling

7.1.1.1. Acoustic simulations

The acoustic simulations play a central role in articulatory synthesis and should enable the production of all classes of sounds in a realistic manner. The production of voiced fricatives relies on a partial closure of the glottis which simultaneously creates an airflow which generates turbulence downwards from the constriction and the vibration of the vocal folds. Our acoustic simulation framework [14] has been extended to incorporate a glottal chink [29] in a self-oscillating vocal fold model. The glottis is then made up of two main separated components: a self-oscillating part and a constantly open chink. This feature allows the simulation of voiced fricatives, thanks to a self-oscillating model of the vocal folds to generate the voiced source, and the glottal opening that is necessary to generate the frication noise.

The acoustic propagation paradigm is appropriately chosen so that it can deal with complex geometries and a time-varying length of the vocal tract. Temporal scenarios for the dynamic shapes of the vocal tract and the glottal configurations were derived from the simultaneous acquisition of X-ray or MRI images and audio recording. Copy synthesis of a few French sentences [30], [31], [53] shows the accuracy of the simulation framework to reproduce acoustic cues of phrase-level utterances containing most of French phone (sound) classes while considering the real geometric shape of the speaker. For this purpose the articulatory model has been extended to offer a better precision of the epiglottis and of lips.

7.1.1.2. Acquisition of articulatory data

The acquisition of dynamic data is a key objective since speech production gestures involve the anticipation of the articulatory targets of the coming sounds. Cine-MRI represents an invaluable tool since it can image the whole vocal tract. However, speech requires a sampling frequency above 30 Hz to capture interesting information. Compressive sampling relies on partially collecting data in the Fourier space of the images acquired via MRI. The combination of compressed sensing technique, along with homodyne reconstruction, enables the missing data to be recovered [32]. The good reconstruction is guaranteed by an appropriate design of the sampling pattern. It is based on a pseudo-random Cartesian scheme, where each line is partially acquired for use of the homodyne reconstruction, and where the lines are pseudo-randomly sampled: central lines are constantly acquired and the sampling density decreases as the lines are far from the center.

7.1.1.3. Markerless articulatory acquisition techniques

With the spread of depth cameras (kinect-like systems), many researchers consider using these systems to track the movement of some speech articulators as lips and jaw. We are considering using this kind of system if it is suitable for speech production studies. For this reason, we have assessed the precision of markerless acquisition techniques when used to acquire articulatory data for speech production studies [19]. Two different markerless systems have been evaluated and compared to a marker-based one. The main finding is that both markerless systems provide reasonable results during normal speech and the quality is uneven during fast articulated speech. The quality of the data is dependent on the temporal resolution of the markerless system.

7.1.2. Expressive acoustic-visual synthesis

7.1.2.1. Expressive speech

A comparison between emotional and neutral speech was conducted using a small database containing utterances recorded in six emotional types (anger, fear, sadness, disgust, surprise and joy) as well as in a neutral pronunciation. The prosodic analysis focused on the main prosodic parameters such as vowel duration, energy and fundamental frequency (F0) level, and pause occurrences. The values of prosodic parameters were compared among the various emotional styles, as well as between emotional style and neutral style utterances. Moreover, the structuration of the sentences, in the various emotional styles, was particularly studied through a detailed analysis of pause occurrences and their length, and of the length of prosodic groups [23].

7.1.2.2. Expressive acoustic and visual speech

Concerning expressive audiovisual speech synthesis, a case study of a semi-professional actor who uttered a set of sentences for 6 different emotions in addition to neutral speech was conducted. Our purpose is to identify the main characteristics of audiovisual expressions that need to be integrated during synthesis to provide believable emotions to the virtual 3D talking head. We have recorded concurrently audio and motion capture data. The acoustic and the visual data have been analyzed. The main finding is that although some expressions are not well identified, some expressions were well characterized and tied in both acoustic and visual space [40]. The acquisition of the corpus was done with the platform software PLAVIS (cf. 9.2.12).

7.1.3. Categorization of sounds and prosody for native and non-native speech

7.1.3.1. Categorization of sounds for native speech

We examined the schooling experiences of 166 young people with disabilities, aged from 6 to 20 years old. These children and teenagers had specific language impairment : SLI (severe language impairment), dyslexia, dysorthographia. The phonemic discrimination, phonological and phonemic analysis difficulties faced in their childhoods had raised reading difficulties which constituted a major obstacle, which the pupils did not overcome. Consequently, this led them to repeat one or more grades. This rate is 18 times higher than the French average. The importance of this cycle of learning can be better understood through this data, which could also enable, if not overcoming the handicap, to at least improving their learning possibilities [64].

7.1.3.2. Digital books for language impaired children

Three digital albums for language impaired children were designed within the Handicom (ADT funded by Inria). These three prototypes focus on the importance of multimodal speech combining written words and visual clues: a 3D avatar telling the stories and coding oral language in LPC (french cued speech) for hearing impaired children. Eight speech and language therapists used one of these albums (the digital prototype *Nina fête son anniversaire* !) with 8 children who are aged 5 years: 4 hearing impaired children, 2 children with SLI and 2 children with autism. The training they experienced with these children showed that the use of the digital book can foster some capacities involved in language learning [41].

7.1.3.3. Analysis of non-native pronunciations

The IFCASL corpus is a French-German bilingual phonetic learner corpus designed, recorded and annotated in the IFCASL project (cf. 9.2.6). It incorporates data for a language pair in both directions, i.e. in our case French learners of German, and German learners of French. In addition, the corpus is complemented by two sub-corpora of native speech by the same speakers. The corpus has been finalized, and provides spoken data by about 100 speakers with comparable productions, annotated and segmented at the word and phone levels, with more than 50% of manually checked and corrected data [51].

We investigated the correct placement of lexical (German) or post-lexical (French) accents [52]. French and German differ with respect to the representation and implementation of prominence. French can be assumed to have no prominence represented in the mental lexicon and accents are regularly assigned post-lexically on the last full vowel of an accentual group. In German, prominence is considered to be represented lexically. This difference may give rise to interferences when German speakers learn French and French speakers learn German. Results of a judgment task (conducted with 3 trained phoneticians) of native and nonnative productions of French learners of German and German learners of French, all of them beginners, show that both groups have not completely acquired the correct suprasegmental structures in the respective L2 [0], since both groups are worse concerning the correct placement of prominence than the native speakers. Furthermore, the results suggest that the native pattern is one of the most important factors for wrong prominence placements in the foreign language, e.g., if the prominence placement of L1 and L2 coincide, speakers produce the smallest amount of errors. Finally, results indicate that visual display of accented syllables increases the likelihood of a correct accent placement.

7.1.3.4. Implementation of acoustic feedback for devoicing of final fricatives

In view of implementing acoustic feedback in foreign language learning we analyzed acoustic cues which could explain that final fricatives are perceived as voiced or unvoiced. The ratio of unvoiced frames in the consonantal segment and also the ratio between consonantal duration and vowel duration were measured. As expected, we found that beginners face more difficulties to produce voiced fricatives than advanced learners. Also, the production becomes easier for the learners, especially for beginners, if they practice repetition after a native speaker. We use these findings to design and develop feedback via speech analysis/synthesis technique TD-PSOLA using the learner's own voice and voiced fricatives uttered by French speakers [36]. We selected fully voiced exemplars and evaluated whether the presence of an additional schwa fosters the perception of voicing by native French speakers.

7.2. Statistical Modeling of Speech

Participants: Antoine Liutkus, Emmanuel Vincent, Irène Illina, Dominique Fohr, Denis Jouvet, Vincent Colotte, Ken Deguernel, Mathieu Fontaine, Amal Houidhek, Aditya Nugraha, Imran Sheikh, Imene Zangar, Mohamed Bouallegue, Sunit Sivasankaran.

7.2.1. Source separation

7.2.1.1. Deep neural models for source separation

We pursued our research on the use of deep learning for multichannel source separation [18]. Our technique exploits both the spatial properties of the sources as modeled by their spatial covariance matrices and their spectral properties as modeled by a deep neural network. The model parameters are alternately estimated in an expectation-maximization (EM) fashion. We used this technique for music separation in the context of the 2016 Signal Separation Evaluation Campaign (SiSEC) [39]. We also used deep learning to address the fusion of multiple source separation techniques and found it to perform much better than the variational Bayesian model averaging techniques previously investigated [17].

We wrote an article about music source separation for the general public [59].

7.2.1.2. α-stable modeling of audio signals

The alpha-harmonizable model has recently been proposed by A. Liutkus et al. [66] as the only available probabilistic framework to account for signal processing methods manipulating fractional spectrograms instead of more traditional power spectrograms. Indeed, they generalize the classical Gaussian formulation and permit to handle large uncertainties or signal dynamics, which are both common in audio.

[0] L2 indicates the non-native language, whereas L1 indicates the native language

Our work on this topic this year has notably focused on its extension to the multichannel setting, which is important for music processing and source localization. Since inference in multivariate alpha-stable distribution is a very intricate issue, the approach undertaken has focused on analysing the multichannel signals through the joint analysis of multiple scalar projections on the real line. This results in an original algorithm called PROJET that combines computational tractability with the inherent robustness of alpha-stable models [15], [34].

7.2.2. Acoustic modeling

7.2.2.1. Noise-robust acoustic modeling

In many real-world conditions, the target speech signal is reverberated and noisy. In order to motivate further work by the community, we created an international evaluation campaign on that topic in 2011: the CHiME Speech Separation and Recognition Challenge. After three successful editions [11], [55], we organized the fourth edition in 2016. We also summarized the speech distortion conditions in real scenarios for speech processing applications [42] and collected a French corpus for distant-microphone speech processing in real homes [24].

Speech enhancement and automatic speech recognition (ASR) are most often evaluated in matched (or multi-condition) settings where the acoustic conditions of the training data match (or cover) those of the test data. We conducted a systematic assessment of the impact of acoustic mismatches (noise environment, microphone response, data simulation) between training and test data on the performance of recent DNN-based speech enhancement and ASR techniques [21]. The results show that most algorithms perform consistently on real and simulated data and are barely affected by training on different noise environments. This suggests that DNNs generalize more easily than previously thought.

7.2.2.2. Environmental sounds

We explored acoustic modeling for the classification of environmental sound events and sound scenes and submitted our system to the DCASE 2016 Challenge [33].

7.2.3. Linguistic modeling

7.2.3.1. Out-of-vocabulary proper name retrieval

The diachronic nature of broadcast news causes frequent variations in the linguistic content and vocabulary, leading to the problem of Out-Of-Vocabulary (OOV) words in automatic speech recognition. Most of the OOV words are found to be proper names whereas proper names are important for automatic indexing of audio-video content as well as for obtaining reliable automatic transcriptions. New proper names missed by the speech recognition system can be recovered by a dynamic vocabulary multi-pass recognition approach in which new proper names are added to the speech recognition vocabulary based on the context of the spoken content [47]. The goal of this work is to model the semantic and topical context of new proper names in order to retrieve OOV words which are relevant to the spoken content in the audio document. Probabilistic topic models [44] and word embeddings from neural network models are explored for the task of retrieval of relevant proper names. Neural network context models trained with an objective to maximise the retrieval performance are proposed. A Neural Bag-of-Words (NBOW) model trained to learn context vector representations at a document level is shown to outperform the generic representations. The proposed Neural Bag-of-Weighted-Words (NBOW2) model learns to assign a degree of importance to input words and has the ability to capture task specific key-words [46] [45]. Experiments on automatic speech recognition of French broadcast news videos demonstrate the effectiveness of the proposed models. Further evaluation of the NBOW2 model on standard text classification tasks, including movie review sentiment classification and newsgroup topic classification, shows that it learns interesting information about the task and gives the best classification accuracies among the bag-of-words models.

7.2.3.2. Adding words in a language model

Out-of-vocabulary (OOV) words can pose a particular problem for automatic speech recognition of broadcast news. The language models (LMs) of ASR systems are typically trained on static corpora, whereas new words (particularly new proper nouns) are continually introduced in the media. Additionally, such OOVs are often content-rich proper nouns that are vital to understanding the topic. We explore methods for dynamically adding OOVs to language models by adapting the n-gram language model used in our ASR system. We propose two strategies: the first one relies on finding in-vocabulary (IV) words similar to the OOVs, where word embeddings are used to define similarity. Our second strategy leverages a small contemporary corpus to estimate OOV probabilities. The models we propose yield improvements in perplexity over the baseline; in addition, the corpus-based approach leads to a significant decrease in proper noun error rate over the baseline in recognition experiments [26].

7.2.3.3. Music language modeling

Similarly to speech, music involves several levels of information, from the acoustic signal up to cognitive quantities such as composer style or key, through mid-level quantities such as a musical score or a sequence of chords. The dependencies between mid-level and lower- or higher-level information can be represented through acoustic models and language models, respectively. We published two articles that summarize our work on the System & Contrast model for the characterization of the mid-term and long-term structure of music [12] and on the structural segmentation of popular music pieces using a regularity constraint that naturally stems from this model [20], [58]. We also proposed a new model for automatic music improvisation that combines a multi-dimensional probabilistic model encoding the musical experience of the system and a factor oracle encoding the local context of the improvisation [27].

7.2.4. Speech generation by statistical methods

Work on HMM-based Arabic speech synthesis was carried out within a CMCU PHC project with ENIT (Engineer school at Tunis-Tunisia; cf. 9.4.2.2). A first version of the system, based on the HTS toolkit (HMM-based Speech Synthesis System), is now working; and the study of the impact of some parameters is ongoing.

In parallel, the HTS system is also applied to the French language.

7.3. Uncertainty Estimation and Exploitation in Speech Processing

Participants: Emmanuel Vincent, Odile Mella, Dominique Fohr, Denis Jouvet, Baldwin Dumortier, Juan Andres Morales Cordovilla, Karan Nathwani, Ismaël Bada.

7.3.1. Uncertainty and acoustic modeling

7.3.1.1. Uncertainty in noise-robust speech and speaker recognition

In many real-world conditions, the target speech signal overlaps with noise and some distortion remains after speech enhancement. The framework of uncertainty decoding assumes that this distortion has a Gaussian distribution and seeks to estimate its covariance matrix in order to exploit it for subsequent feature extraction and decoding. A number of uncertainty estimators have been proposed in the literature, which are typically based on fixed mathematical approximations or heuristics. We finalized our work on a principled variational Bayesian approach to uncertainty estimation and showed its benefit w.r.t. other estimators for speech and speaker recognition [9]. We also pursued our work on the propagation of uncertainty in deep neural network acoustic models.

7.3.1.2. Uncertainty in other applications

Besides the above applications, we pursued our exploration of uncertainty modeling for robot audition and wind turbine control. In the first context, uncertainty arises about the location of acoustic sources and the robot is controlled to locate the sources as quickly as possible [38]. In the second context, uncertainty arises about the noise intensity of each wind turbine and the turbines are controlled to maximize electrical production under a maximum noise threshold [62].

7.3.2. Uncertainty and phonetic segmentation

7.3.2.1. Speech-text alignment

We have continued our work on determining more accurate phonetic boundaries with two new approaches based on DNN. The first approach proposes to find phonetic boundaries directly from the parameterized speech signal using an LSTM (Long Short-Term Memory) neural network. The aim of the second approach is twofold: provide confidence measures for evaluating speech-text alignment outputs and refine these outputs. One of these studies was done with the Synalp team of LORIA in the framework of the project ORFEO (cf. 9.2.5). The achieved confidence measure outperforms a confidence score (based on acoustic posterior probability) derived from a state-of-the-art text-to-speech aligner [43].

Within the IFCASL project (cf. 9.2.6), we have also developed a speech-text alignment system for German which will be integrated into the ASTALI software.

7.3.3. Uncertainty and prosody

The study of discourse particles that was initiated last year, has continued in the framework of the CPER LCHN (cf. 9.1.2). A larger set of words and expressions that can be used either as normal lexical words or as discourse particles (as for example *quoi* (what), *voilà* (there it is), ...) has been considered. For each of these words/expressions and for each speech corpus that was aligned in the ORFEO project (cf. 9.2.5), a subset of about one hundred occurrences were selected. Thanks to the CPER LCHN support, a part of these occurrences have been annotated as "discourse particle" or "non discourse particle". Detailed analysis is in progress, with respect to the function (discourse particle or not), the type of speech corpus, and the associated prosodic features.

The fundamental frequency is one of the prosodic features. Numerous approaches exist for the computation of F0. Most of them lead to good performance on good quality speech. The performance degradation with respect to noise level has been studied on reference databases, for several (about ten) F0 detection approaches. It was observed that for each algorithm, a large part of the errors are due to incorrect voiced/unvoiced decision. Studies have also been initiated for computing a confidence measure on the estimated F0 values through the use of neural network approaches.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. Venathec

Company: Venathec SAS

Other partners: ACOEM Group, GE Intelligent Platforms (contracted directly with Venathec)

Duration: June 2014 - August 2017

Supported by: Bpifrance

Abstract: The project aims to design a real-time control system for wind farms that will maximize energy production while limiting sound nuisance. This will leverage our know-how on audio source separation and uncertainty modeling and propagation.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. COREXp

Project acronym: CORExp

Project title: Acquisition, Processing and Analysis of a Corpus for the Synthesis of Expressive Audiovisual Speech

Duration: December 2014 - December 2016

Coordinator: Slim Ouni

Cofunded by Inria and Région Lorraine

Abstract: The main objective of this project was the acquisition of a bimodal corpus of a considerable size (several thousand sentences) to study the expressiveness and emotions during speech (for example, how to decode facial expressions that are merged with speech signals). The main purpose was to acquire, process and analyze the corpus and to study the expressiveness; the results will be used for the expressive audiovisual speech synthesis system.

9.1.2. CPER LCHN

Project acronym: CPER LCHN

Project title: CPER "Langues, Connaissances et Humanités Numériques"

Duration: 2015-2020

Coordinator: Bruno Guillaume (LORIA) & Alain Polguère (ATILF)

Abstract: The main goal of the project is related to experimental platforms for supporting research activities in the domain of languages, knowledge and numeric humanities engineering.

MULTISPEECH contributes to automatic speech recognition, speech-text alignment and prosody aspects.

9.1.3. CPER IT2MP

Project acronym: CPER IT2MP

Project title: CPER "Innovation Technologique Modélisation et Médecine Personalisée"

Duration: 2015-2020

Coordinator: Faiez Zannad (Inserm-CHU-UL)

Abstract: The goal of the project is to develop innovative technologies for health, and tools and strategies for personalized medicine.

MULTISPEECH will investigate acoustic monitoring using an array of microphones.

9.1.4. SATT Dynalips

Project title: Control of the movements of the lips in the context of facial animation for an intelligible lipsync.

Duration: May 2016 - December 2017

Coordinator: Slim Ouni

Abstract: We propose in this project the development of tools of lipsync which from recorded speech will provide realistic mechanisms of animating the lips. These tools will be available to be integrated into existing 3D animation software and existing game engines. One objective is that these lipsync tools fit easily into the production pipeline in the field of 3D animation and video games. The goal of this maturation is to propose a product ready to be exploited in the industry whether by the creation of a start-up or by the distribution of licenses.

9.2. National Initiatives

9.2.1. EQUIPEX ORTOLANG

Project acronym: ORTOLANG [0]

[0] http://www.ortolang.fr

Project title: Open Resources and TOols for LANGuage

Duration: September 2012 - December 2016 (phase I)

Coordinator: Jean-Marie Pierrel, ATILF (Nancy)

Other partners: LPL (Aix en Provence), LORIA (Nancy), Modyco (Paris), LLL (Orléans), INIST (Nancy)

Abstract: The aim of ORTOLANG was to propose a network infrastructure offering a repository of language data (corpora, lexicons, dictionaries, etc.) and tools and their treatment that are readily available and well-documented. This will enable a real mutualization of analysis research, of modeling and automatic treatment of the French language. This will also facilitate the use and transfer of resources and tools set up within public laboratories towards industrial partners, in particular towards SME which often cannot develop such resources and tools for language treatment due to the costs of their realization. Moreover, this will promote the French language and local languages of France by sharing knowledge which has been acquired by public laboratories.

Several teams of the LORIA laboratory contribute to this Equipex, mainly with respect to providing tools for speech and language processing. MULTISPEECH contributes with text-speech alignment and speech visualization tools.

9.2.2. E-FRAN METAL

Project acronym: E-FRAN METAL

Project title: Modèles Et Traces au service de l'Apprentissage des Langues

Duration: October 2016 - September 2020

Coordinator: Anne Boyer (LORIA)

Other partners: Interpsy, LISEC, ESPE de Lorraine, D@NTE (Univ. Versailles Saint Quentin), Sailendra SAS, ITOP Education, Rectorat.

Abstract: METAL aims at improving the learning of languages (both written and oral components) through the development of new tools and the analysis of numeric traces associated with students' learning, in order to adapt to the needs and rythm of each learner.

Multispeech is concerned by oral language learning aspects.

9.2.3. PIA2 ISITE LUE

Project acronym: ISITE LUE

Project title: Lorraine Université d'Excellence

Duration: starting in 2016

Coordinator: Univ. Lorraine

Abstract: The initiative aims at developing and densifying the initial perimeter of excellence, within the scope of the social and economic challenges, so as to build an original model for a leading global engineering university, with a strong emphasis on technological research and education through research. For this, we have designed LUE as an “engine” for the development of excellence, by stimulating an original dialogue between knowledge fields.

MULTISPEECH is mainly concerned with challenge number 6: "Knowledge engineering", i.e., engineering applied to the field of knowledge and language, which represent our immaterial wealth while being a critical factor for the consistency of future choices. In 2016, this project has funded a new PhD thesis.

9.2.4. ANR ContNomina

Project acronym: ContNomina

Project title: Exploitation of context for proper names recognition in diachronic audio documents

Duration: February 2013 - March 2017

Coordinator: Irina Illina

Other partners: LIA, Synalp

Abstract: The ContNomina project focuses on the problem of proper names in automatic audio processing systems by exploiting in the most efficient way the context of the processed documents. To do this, the project addresses the statistical modeling of contexts and of relationships between contexts and proper names; the contextualization of the recognition module (through the dynamic adjustment of the lexicon and of the language model in order to make them more accurate and certainly more relevant in terms of lexical coverage, particularly with respect to proper names); and the detection of proper names (on the one hand, in text documents for building lists of proper names, and on the other hand, in the output of the recognition system to identify spoken proper names in the audio/video data).

9.2.5. ANR ORFEO

Project acronym: ORFEO [0]

Project title: Outils et Ressources pour le Français Écrit et Oral

Duration: February 2013 - February 2016

Coordinator: Jeanne-Marie DEBAISIEUX (Université Paris 3)

Other partners: ATILF, CLLE-ERSS, ICAR, LIF, LORIA, LATTICE, MoDyCo

Abstract: The main objective of the ORFEO project is the constitution of a corpus for the study of contemporary French.

In this project, we were concerned by the automatic speech-text alignment at the word and phoneme levels for audio files from several corpora gathered by the project. These corpora orthographically transcribed with Transcriber contain mainly spontaneous speech, recorded under various conditions with a large SNR range and a lot of overlapping speech and anonymised speech segments. For the forced speech-text alignment phase, we applied our 2-step methodology (the first step uses a detailed acoustic model for finding the pronunciation variants; then, in the second step a more compact model is used to provide more temporally accurate boundaries).

9.2.6. ANR-DFG IFCASL

Project acronym: IFCASL

Project title: Individualized feedback in computer-assisted spoken language learning

Duration: March 2013 - December 2016

Coordinator: Jürgen Trouvain (Saarland University)

Other partners: Saarland University (COLI department)

Abstract: The main objective of IFCASL is to investigate learning of oral French by German speakers, and oral German by French speakers at the phonetic level.

A French-German learner corpus was designed and recorded. French speakers were recorded in Nancy, whereas German speakers were recorded in Saarbrücken. An automatic speech-text alignment process was applied on all the data. Then, the French speech data (native and non-native) were manually checked and annotated in France, and the German speech data (native and non-native) were manually checked and annotated in Germany. The corpora are currently used for analyzing non-native pronunciations, and studying feedback procedures.

[0] http://www.agence-nationale-recherche.fr/en/anr-funded-project/?tx_lwmsuivibilan_pi2[CODE]=ANR-12-CORP-0005

9.2.7. ANR DYCI2

Project acronym: DYCI2 [0]

Project title: Creative Dynamics of Improvised Interaction

Duration: March 2015 - February 2018

Coordinator: Ircam (Paris)

Other partners: Inria (Nancy), University of La Rochelle

Abstract: The goal of this project is to design a music improvisation system which will be able to listen to the other musicians, improvise in their style, and modify its improvisation according to their feedback in real time.

9.2.8. ANR JCJC KAMoulox

Project acronym: KAMoulox

Project title: Kernel additive modelling for the unmixing of large audio archives

Duration: January 2016 - January 2019

Coordinator: Antoine Liutkus

Abstract: Develop the theoretical and applied tools required to embed audio denoising and separation tools in web-based audio archives. The applicative scenario is to deal with large audio archives, and more precisely with the notorious "Archives du CNRS — Musée de l'homme", gathering about 50,000 recordings dating back to the early 1900s.

9.2.9. ANR ArtSpeech

Project acronym: ArtSpeech

Project title: Synthèse articulatoire phonétique

Duration: October 2015 - March 2019

Coordinator: Yves Laprie

Other partners: Gipsa-Lab (Grenoble), IADI (Nancy), LPP (Paris)

Abstract: The objective is to synthesize speech from text via the numerical simulation of the human speech production processes, i.e. the articulatory, aerodynamic and acoustic aspects. Corpus based approaches have taken a hegemonic place in text to speech synthesis. They exploit very good acoustic quality speech databases while covering a high number of expressions and of phonetic contexts. This is sufficient to produce intelligible speech. However, these approaches face almost insurmountable obstacles as soon as parameters intimately related to the physical process of speech production have to be modified. On the contrary, an approach which rests on the simulation of the physical speech production process makes explicitly use of source parameters, anatomy and geometry of the vocal tract, and of a temporal supervision strategy. It thus offers direct control on the nature of the synthetic speech.

Measurements of glottis opening during the production of fricatives via EPGG (ElectroPhotoGlottoGraphy), the design of acoustic experiments with a replica of the vocal tract and the design of dynamic acquisition with MRI were the main activities of this first year.

9.2.10. FUI RAPSODIE

Project acronym: RAPSODIE

Project title: Automatic Speech Recognition for Hard of Hearing or Handicapped People

Duration: March 2012 - February 2016

Coordinator: eRocca (Mieussy, Haute-Savoie)

[0] http://repmus.ircam.fr/dyci2/

Other partners: CEA (Grenoble), Inria (Nancy), CASTORAMA (France)

Abstract: The goal of the project was to realize a portable device to help a hard-of-hearing person to communicate with other people. To achieve this goal the portable device needs to access a speech recognition system, adapted to this task. Another application of the device is environment vocal control for handicapped persons.

In this project, MULTISPEECH was involved in optimizing the speech recognition models for the envisaged task, and in finding the best way of presenting the speech recognition results in order to maximize the communication efficiency between the hard-of-hearing person and the speaking person.

9.2.11. FUI VoiceHome

Project acronym: VoiceHome

Duration: February 2015 - July 2017

Coordinator: onMobile

Other partners: Orange, Delta Dore, Technicolor Connected Home, eSoftThings, Inria (Nancy), IRISA, LOUSTIC

Abstract: The goal of this project is to design a robust voice control system for smart home and multimedia applications. We are responsible for the robust automatic speech recognition brick.

9.2.12. ADT Plavis

Project acronym: Plavis

Project title: Platform for acquisition and audiovisual speech synthesis

Duration: January 2015 - December 2016

Coordinator: Vincent Colotte

Abstract: The objective of this project was to develop a platform acquisition and audiovisual synthesis system (3D animation of the face synchronously with audio). The main purpose was to build a comprehensive platform for acquisition and processing of audiovisual corpus (selection, acquisition and acoustic processing, 3D visual processing and linguistic processing). The acquisition was performed using a motion-capture system (Kinect-like), a Vicon system, and an electromagnetic articulography (EMA) system.

9.2.13. LORIA exploratory project

Project title: Acquisition and processing of multimodal corpus in the context of interactive human communication

Duration: June 2015 - May 2016

Coordinator: Slim Ouni

Abstract: The aim of this project was the study of the various mechanisms involved in multimodal human communication that can be oral, visual, gestural and tactile. This project focused on the identification and acquisition of a very large corpus of multimodal data from multiple information sources and acquired in the context of interaction and communication between two people or more.

9.2.14. SYNABE

Project acronym: SYNABE

Project title: Articulatory data synchronization for studying stuttering

Duration: January 2016 - December 2016

Coordinator: Fabrice Hirsch (Praxiling, UMR 5267, Montpellier)

Other partners: S. Ouni

Funding: CNRS DEFI Instrumentation aux limites

Abstract: The objective of this project is to use simultaneously three hardware allowing having information on the subglottic (respiratory belt), glottic (electroglottograph) and supraglottic (articulograph) levels during the production of the speech in order to know the timing of the gestures during speech. This system will be used to study the motor coordination between the three levels mentioned in the stuttering and normo-fluent words. We will propose a new typology of normal and pathological disfluencies.

Our main contribution concerned the articulatory data acquisition using the articulograph AG501.

9.3. European Initiatives

9.3.1. Collaborations with Major European Organizations

Jon Barker: University of Sheffield (UK)

Robust speech recognition [11], [55]

9.4. International Initiatives

9.4.1. Inria International Partners

9.4.1.1. Informal International Partners

Jonathan Le Roux, Shinji Watanabe, John R. Hershey: Mitsubishi Electric Research Labs (MERL, Boston, USA)

Robust speech recognition [11], [55]

Dayana Ribas Gonzalez, Ramón J. Calvo: CENATAV (Habana, Cuba)

Robust speaker recognition [42]

9.4.2. Participation in Other International Programs

9.4.2.1. STIC-AmSud - multimodal communication corpus

STIC-AmSud: MCC - Multimodal Communication Corpus. A collaboration: Argentina, Chile and France (01/2015-12/2016)

Project acronym: MCC

Project title: Multimodal Communication Corpus

Duration: January 2015 - December 2016

International Coordinator: S. Ouni

National Coordinators: Nancy Hitschfeld (Depto. de Ciencias de la Computación (DCC), Universidad de Chile) - Chile; and, Juan Carlos Gomez (Centro Internacional Franco Argentino de Ciencias de la Información y de Sistemas (CIFASIS), UNR, CONICET) - Argentina

Abstract: The project aims to collect a multimodal speech corpus containing synchronized audiovisual data recorded from talking individuals. The corpus will incorporate several communication modes which appear in the communication among humans, such as the acoustic signal, facial movements and body gestures during speech. During 2016, a complete corpus of 8 speakers (4 French and 4 Spanish) has been acquired and processed. The corpus will be distributed using the Ortolang platform.

9.4.2.2. PHC UTIQUE - HMM-based Arabic speech synthesis

PHC UTIQUE - HMM-based Arabic speech synthesis, with ENIT (Engineer school at Tunis-Tunisia)

Duration: 2015 - 2018.

Coordinators: Vincent Colotte (France) and Noureddine Ellouze (Tunisia).

Abstract: Development of an HMM-based speech synthesis system for the Arabic language. This includes the development of an Arabic speech corpus, the selection of linguistic features relevant to Arabic HMM-based speech synthesis, as well as improving the quality of the speech signal generated by the system.

9.5. International Research Visitors

9.5.1. Visits of International Scientists

Sebastian Gonzales Mora

Date: Jan 2016

Faculty de Cs. Físicas y Matemáticas, University of Chile

Benjamin Martinez Elizalde

Date: May 2016 - Aug 2016

Institution: Carnegie Mellon University (USA)

Dayana Ribas Gonzalez

Date: Sep 2016 - Dec 2016

Institution: CENATAV (Cuba)

Ziteng Wang

Date: Sep 2016 - Sep 2017

Institution: Institute of Acoustics, Chinese Academy of Sciences (China)

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

General co-chair, 4th CHiME Speech Separation and Recognition Challenge (E. Vincent)

General co-chair, 4th International Workshop on Speech Processing in Everyday Environments, San Francisco, USA, September 2016 (E. Vincent)

General co-chair, 14th International Conference on Auditory-Visual Speech Processing, Stockholm, Sweden August 2017 (S. Ouni)

Chair, SiSEC 2016, Signal Separation Evaluation Challenge (A. Liutkus)

Elected chair, Steering Committee of the Latent Variable Analysis and Signal Separation (LVA/ICA) conference series (E. Vincent)

Chair, Challenges Subcommittee, IEEE Technical Committee on Audio and Acoustic Signal Processing (E. Vincent)

10.1.1.2. Member of the Organizing Committees

Member of the organizing committee, 2017 IEEE Automatic Speech Recognition and Understanding Workshop, Okinawa, Japan, December 2017 (E. Vincent)

Member of the steering committee, Detection and Classification of Acoustic Scenes and Events (DCASE) challenge series (E. Vincent)

10.1.1.3. Member of the Conference Program Committees

Area chair for Analysis of Speech and Audio Signal, INTERSPEECH'2016 (D. Jouvet)

Area chair for Audio and Speech Source Separation, IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP) (E. Vincent)

10.1.1.4. Reviewer

CHiME 2016 - Speech Separation and Recognition Challenge (E. Vincent)

EUSIPCO 2016 - European Signal Processing Conference (D. Jouvet)

ICECS 2016 - Conference on Environmental and Computer Science (R. Serizel)

INTERSPEECH 2016 (A. Bonneau, S.Ouni, E. Vincent, I. Illina, Y. Laprie)

IROS 2016 - International Conference on Intelligent Robots and Systems (E. Vincent)

IVA 2016 - International Conference on Intelligent Virtual Agents (S. Ouni)

JEP 2016 - Journées d'Etudes sur la Parole (D. Jouvet, A. Bonneau, E. Vincent, D. Fohr, I. Illina, O. Mella, Y. Laprie)

SLT 2016 - IEEE Spoken Language Technology Workshop (E. Vincent)

10.1.2. Journal

10.1.2.1. Member of the Editorial Boards

Computer Speech and Language, special issue on Multi-Microphone Speech Recognition in Everyday Environments (E. Vincent)

Speech Communication (D. Jouvet)

Traitement du signal (E. Vincent)

International Journal of Learner Corpus Research, special issue on "Investigating segmental, prosodic and fluency features in spoken learner corpora" (A. Bonneau, Guest Editor)

Speech Communication, special issue on Realism in Robust Speech and Language Processing (E. Vincent)

10.1.2.2. Reviewer - Reviewing Activities

Computer Speech and Language (D. Jouvet, S. Ouni, E. Vincent)

Digital Signal Processing (E. Vincent)

IEEE Transactions on Audio, Speech and Language Processing (A. Liutkus, S. Ouni, R. Serizel)

IEEE Transactions on Signal Processing (A. Liutkus)

IEEE Signal Processing Letters (A. Liutkus, R. Serizel)

Journal of the Acoustical Society of America (Y. Laprie)

JASA Express Letters (Y. Laprie)

Speech Communication (E. Vincent, Y. Laprie)

10.1.3. Invited Talks

Séparation de sources: quand l'acoustique rencontre le machine learning, keynote talk, 13e Congrès Français d'Acoustique (E. Vincent) [22]

Speech recognition, Ecole Nationale d'Ingénieurs de Tunis, May 2016 (D. Jouvet)

Les corpus acoustiques et langagiers pour la reconnaissance de la parole, Seminar about Big Data, LIA-LINOS (Laboratoire International Associé), May 2016 (O. Mella)

Parole audiovisuelle : pour faciliter la communication parlée, Praxiling, Université de Montpellier 3, October 2016 (S. Ouni)

10.1.4. Leadership within the Scientific Community

Elected chair, ISCA Special Interest Group on Robust Speech Processing (E. Vincent)

Secretary/Treasurer, executive member of AVISA (Auditory-VIsual Speech Association), an ISCA Special Interest Group (S. Ouni)

Member IEEE Technical Committee on Audio and Acoustic Signal Processing (A. Liutkus)

10.1.5. Scientific Expertise

Expertise of an ANR project proposal (D. Jouvet, Y. Laprie, E. Vincent)

Expertise of a project for the Research Foundation Flanders – FWO (S. Ouni)

10.1.6. Research Administration

Elected Member of the board of the AM2I Scientific Pole - Université de Lorraine (Y. Laprie)

Member of the HCERES visiting committee for LIUM (D. Jouvet)

Chairman of selection committee for the position of Assistant Professor (ESSTIN 0762, May 2016), Y. Laprie.

Member of a selection committee (Université d'Avignon, May 2016), E. Vincent

Member of a selection committee (Université du Maine, May 2016), D. Jouvet

Member of a selection committee (Télécom ParisTech, June 2016), E. Vincent

Member of the "Commission de développement technologique" (A. Bonneau)

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

DUT: I. Illina, Programming in Java, 150 hours, L1, University of Lorraine, France

DUT: I. Illina, Linux System, 65 hours, L1, University of Lorraine, France

DUT: I. Illina, Supervision of student projects and stages, 50 hours, L2, University of Lorraine, France

DUT: S. Ouni, Programming in Java, 24 hours, L1, University of Lorraine, France

DUT: S. Ouni, Web Programming, 24 hours, L1, University of Lorraine, France

DUT: S. Ouni, Graphical User Interface, 96 hours, L1, University of Lorraine, France

DUT: S. Ouni, Advanced Algorihms, 24 hours, L2, University of Lorraine, France

DUT: R. Serizel, Introduction to computer tools, 108h, L1, University of Lorraine – IUT Nancy Charlemagne, France

Licence: V. Colotte, C2i - Certificat Informatique et Internet, 50h, L1, University of Lorraine, France

Licence: V. Colotte, System, 115h, L3, University of Lorraine, France

Licence: O. Mella, C2i - Certificat Informatique et Internet, 28h, L1, University of Lorraine, France

Licence: O. Mella, Introduction to Web Programming, 30h, L1, University of Lorraine, France

Licence: O. Mella, Computer Networking, 80h, L2-L3, University of Lorraine, France

Licence: A. Piquard-Kipffer, Education Sciences, 36h, L1, France

Licence: A. Piquard-Kipffer, Reading and Writing, 27h, L2, Département Orthophonie, University of Lorraine, France

Licence: A. Piquard-Kipffer, Psycholinguistics, 6 hours, L2 Département Orthophonie, University Pierre et Marie Curie-Paris, France

Licence: A. Piquard-Kipffer, Reading and Writing assessment, 10h, L3, Département Orthophonie, University of Lorraine, France

Master: V. Colotte, Introduction to Speech Analysis and Recognition, 18h, M1, University of Lorraine, France

Master: Y. Laprie, Analyse, perception et reconnaissance de la parole, 32 hours, M1, University of Lorraine, France

Master: O. Mella, Computer Networking, 74h, M1, University of Lorraine, France

Master: O. Mella, Introduction to Speech Analysis and Recognition, 12h, M1, University of Lorraine, France

Master: S. Ouni, Multimedia in Distributed Information Systems, 31 hours, M2, University of Lorraine, France

Master: A. Piquard-Kipffer, Dyslexia, 25 hours, M1, Département Orthophonie, University of Lorraine, France

Master: A. Piquard-Kipffer, Reading and writing, 6 hours, M1, Département Orthophonie, University Pierre et Marie Curie-Paris, France

Master: A. Piquard-Kipffer, Deaf People and Reading, 15 hours, M2 Département Orthophonie, University of Lorraine, France

Master: A. Piquard-Kipffer, Psychology, 40 hours, M2, ESPE, University of Lorraine, France

Master: A. Piquard-Kipffer, French Language Didactics, 80 hours, M2, ESPE, University of Lorraine, France

Engineer school: V. Colotte, Conception and developpement in XML, 20h, Bac+3, Telecom Nancy, France

Ecole d'audioprothèse : A. Bonneau, Phonetics, 16 h, University of Lorraine

Doctorat: A. Piquard-Kipffer, Language Pathology - speech and language screening, 15 hours, EHESP, University of Sorbonne- Paris Cité, France

Adults: O. Mella, Computer science courses for seconday school teachers (Informatique et Sciences du Numérique courses) (21h), ESPE of Academy Nancy-Metz, University of Lorraine, France

Other: V. Colotte, Responsible for "Certificat Informatique et Internet" for the University of Lorraine, France (50000 students, 30 departments)

Other: S. Ouni, Responsible of Année Spéciale DUT, University of Lorraine, France

10.2.2. Supervision

PhD: Imran Sheikh, "Exploiting Semantic and Topic Context to Improve Recognition of Proper Names in Diachronic Audio Documents", November 2016, Irina Illina, Dominique Fohr and Georges Linares.

PhD in progress: Baldwin Dumortier, "Contrôle acoustique d'un parc éolien", September 2014, Emmanuel Vincent and Madalina Deaconu.

PhD in progress: Quan Nguyen, "Mapping of a sound environment by a mobile robot", November 2014, Francis Colas and Emmanuel Vincent.

PhD in progress: Aditya Nugraha, "Deep neural networks for source separation and noise-robust speech recognition", January 2015, Antoine Liutkus and Emmanuel Vincent.

PhD in progress: Ken Deguernel, "Apprentissage de structures musicales en situation d'improvisation", March 2015, Emmanuel Vincent and Gérard Assayag.

PhD in progress: Amal Houidhek, "Élaboration et analyse d'une base de parole arabe pour la synthèse vocale", December 2015, Denis Jouvet and Vincent Colotte (France) and Zied Mnasri (Tunisia).

PhD in progress: Imène Zangar, "Amélioration de la qualité de synthèse vocale par HMM pour la parole arabe", December 2015, Denis Jouvet and Vincent Colotte (France) and Zied Mnasri (Tunisia).

PhD in progress: Mathieu Fontaine, "Processus alpha-stable pour le traitement du signal", May 2016, Antoine Liutkus and Roland Badeau (Télécom ParisTech).

PhD in progress: Amine Menacer, "Traduction automatique de vidéos", May 2016, Kamel Smaïli and Denis Jouvet.

PhD in progress: Anastasiia Tsukanova, "Coarticulation modeling in articulatory synthesis", May 2016, Yves Laprie.

PhD in progress: Nathan Libermann, "Deep learning for musical structure analysis and generation", October 2016, Frédéric Bimbot and Emmanuel Vincent.

PhD in progress: Yang Liu, "Merging acquisition and processing of cineMRI of the vocal tract", October 2016, Pierre-André Vuissoz and Yves Laprie.

10.2.3. Participation in HDR and PhD juries

Participation in PhD thesis Jury for David Guennec (Université Rennes 1, September 2016), Y. Laprie.

Participation in PhD thesis Jury for Ugo Marchand (Université Paris 6, November 2016), E. Vincent, reviewer.

Participation in PhD thesis Jury for Joachim Flocon-Cholet (Université Rennes 1, June 2016), E. Vincent, reviewer.

Participation in PhD thesis Jury for Aly Magassouba (Université Rennes 1, December 2016), E. Vincent, reviewer.

Participation in PhD thesis Jury for Diandra Fabre (Université Grenoble Alpes, December 2016), S. Ouni, reviewer.

Participation in PhD thesis Jury for Ivana Didirková (Université Montpellier 3, December 2016), Y. Laprie, reviewer.

10.2.4. Participation in other juries

Chairman of Scientific « Baccalauréat », specialty Earth Sciences (Académie de Nancy-Metz and Université de Lorraine, July 2016), A. Piquard-Kipffer.

Participation in the Competitive Entrance Examination into Speech-Language Pathology Departement (University of Lorraine, June 2016), A. Piquard-Kipffer.

10.3. Popularization

Demonstration at Village Sciences LORIA, March 2016 (K. Deguernel, E. Vincent, S. Ouni).

Demonstration at Forum des métiers, Collège Peguy, Le Chesnay, March 2016 (A. Piquard-Kipffer).

Demonstration at EHESP-University of Sorbonne- Paris Cité, March 2016 (A. Piquard-Kipffer).

Demonstration at LORIA's 40th Anniversary, June 2016 (K. Deguernel, E. Vincent).

"Démixer la musique", Interstices, January 2016 (A. Liutkus and E. Vincent).

Intervention lors d'une action pour la Maison pour la Science en Lorraine au service des professeurs (A. Bonneau)

Démonstration lors de la journée Rencontre Inria Industrie sur le thème « Ed-Techs au service de e-Education », December 2016 (D. Jouvet)

11. Bibliography

Major publications by the team in recent years

[1] F. BAHJA, J. DI MARTINO, E. H. IBN ELHAJ, D. ABOUTAJDINE.*An overview of the CATE algorithms for real-time pitch determination*, in "Signal, Image and Video Processing", 2013 [*DOI :* 10.1007/s11760-013-0488-4], https://hal.inria.fr/hal-00831660.

[2] J. BARKER, E. VINCENT, N. MA, H. CHRISTENSEN, P. GREEN.*The PASCAL CHiME Speech Separation and Recognition Challenge*, in "Computer Speech and Language", February 2013, vol. 27, n^o 3, p. 621-633 [*DOI :* 10.1016/J.CSL.2012.10.004], https://hal.inria.fr/hal-00743529.

[3] A. BONNEAU, D. FOHR, I. ILLINA, D. JOUVET, O. MELLA, L. MESBAHI, L. OROSANU.*Gestion d'erreurs pour la fiabilisation des retours automatiques en apprentissage de la prosodie d'une langue seconde*, in "Traitement Automatique des Langues", 2013, vol. 53, n^o 3, https://hal.inria.fr/hal-00834278.

[4] D. JOUVET, D. FOHR.*Combining Forward-based and Backward-based Decoders for Improved Speech Recognition Performance*, in "InterSpeech - 14th Annual Conference of the International Speech Communication Association - 2013", Lyon, France, August 2013, https://hal.inria.fr/hal-00834282.

[5] A. OZEROV, M. LAGRANGE, E. VINCENT.*Uncertainty-based learning of acoustic models from noisy data*, in "Computer Speech and Language", February 2013, vol. 27, n^o 3, p. 874-894 [*DOI :* 10.1016/J.CSL.2012.07.002], https://hal.inria.fr/hal-00717992.

[6] A. OZEROV, E. VINCENT, F. BIMBOT.*A General Flexible Framework for the Handling of Prior Information in Audio Source Separation*, in "IEEE Transactions on Audio, Speech and Language Processing", May 2012, vol. 20, n^o 4, p. 1118 - 1133, 16, https://hal.archives-ouvertes.fr/hal-00626962.

[7] A. PIQUARD-KIPFFER, L. SPRENGER-CHAROLLES.*Predicting reading level at the end of Grade 2 from skills assessed in kindergarten: contribution of phonemic discrimination (Follow-up of 85 French-speaking children from 4 to 8 years old)*, in "Topics in Cognitive Psychology", 2013, https://hal.inria.fr/hal-00833951.

Publications of the year

Doctoral Dissertations and Habilitation Theses

[8] I. SHEIKH. *Exploiting Semantic and Topic Context to Improve Recognition of Proper Names in Diachronic Audio Documents*, Université de Lorraine, November 2016, https://hal.archives-ouvertes.fr/tel-01400694.

Articles in International Peer-Reviewed Journal

[9] K. ADILOĞLU, E. VINCENT.*Variational Bayesian Inference for Source Separation and Robust Feature Extraction*, in "IEEE Transactions on Audio Speech and Language Processing", June 2016 [*DOI :* 10.1109/TASLP.2016.2583794], https://hal.inria.fr/hal-00726146.

[10] M. ARON, M.-O. BERGER, E. KERRIEN, B. WROBEL-DAUTCOURT, B. POTARD, Y. LAPRIE.*Multimodal acquisition of articulatory data: Geometrical and temporal registration*, in "Journal of the Acoustical Society of America", 2016, vol. 139, n^o 2, 13 [*DOI :* 10.1121/1.4940666], https://hal.inria.fr/hal-01269578.

[11] J. BARKER, R. MARXER, E. VINCENT, S. WATANABE.*The third 'CHIME' speech separation and recognition challenge: Analysis and outcomes*, in "Computer Speech and Language", October 2016, https://hal.inria.fr/hal-01382108.

[12] F. BIMBOT, E. DERUTY, G. SARGENT, E. VINCENT.*System & Contrast : A Polymorphous Model of the Inner Organization of Structural Segments within Music Pieces*, in "Music Perception", 2016, 41, https://hal.inria.fr/hal-01188244.

[13] M. CADOT, Y. LAPRIE.*Extraction d'un modèle articulatoire à partir d'une analyse tri-directionnelle de cinéradiographies d'un locuteur*, in "Revue des Nouvelles Technologies de l'Information", 2016, vol. Fouille de Données Complexes, n° RNTI-E-31, p. 73-92, https://hal.archives-ouvertes.fr/hal-01346987.

[14] B. ELIE, Y. LAPRIE.*Extension of the single-matrix formulation of the vocal tract: consideration of bilateral channels and connection of self-oscillating models of the vocal folds with a glottal chink*, in "Speech Communication", September 2016, vol. 82, p. 85-96 [*DOI :* 10.1016/J.SPECOM.2016.06.002], https://hal.archives-ouvertes.fr/hal-01199792.

[15] D. FITZGERALD, A. LIUTKUS, R. BADEAU.*Projection-based demixing of spatial audio*, in "IEEE Transactions on Audio, Speech and Language Processing", May 2016, https://hal.inria.fr/hal-01260588.

[16] S. GANNOT, E. VINCENT, S. MARKOVICH-GOLAN, A. OZEROV.*A consolidated perspective on multi-microphone speech enhancement and source separation*, in "IEEE/ACM Transactions on Audio, Speech and Language Processing", December 2016, https://hal.inria.fr/hal-01414179.

[17] X. JAUREGUIBERRY, E. VINCENT, G. RICHARD.*Fusion methods for speech enhancement and audio source separation*, in "IEEE Transactions on Audio, Speech and Language Processing", April 2016, https://hal.archives-ouvertes.fr/hal-01120685.

[18] A. A. NUGRAHA, A. LIUTKUS, E. VINCENT.*Multichannel audio source separation with deep neural networks*, in "IEEE/ACM Transactions on Audio, Speech, and Language Processing", June 2016, vol. 24, n° 10, p. 1652-1664 [*DOI :* 10.1109/TASLP.2016.2580946], https://hal.inria.fr/hal-01163369.

[19] S. OUNI, S. DAHMANI.*Is markerless acquisition of speech production accurate ?*, in "Journal of the Acoustical Society of America", May 2016, vol. 139, n° 6, https://hal.inria.fr/hal-01315579.

[20] G. SARGENT, F. BIMBOT, E. VINCENT.*Estimating the structural segmentation of popular music pieces under regularity constraints*, in "IEEE/ACM Transactions on Audio, Speech, and Language Processing", 2017, https://hal.inria.fr/hal-01403210.

[21] E. VINCENT, S. WATANABE, A. A. NUGRAHA, J. BARKER, R. MARXER.*An analysis of environment, microphone and data simulation mismatches in robust speech recognition*, in "Computer Speech and Language", November 2016, https://hal.inria.fr/hal-01399180.

Invited Conferences

[22] E. VINCENT.*Séparation de sources: quand l'acoustique rencontre le machine learning*, in "13e Congrès Français d'Acoustique", Le Mans, France, April 2016, https://hal.inria.fr/hal-01398720.

International Conferences with Proceedings

[23] K. BARTKOVA, D. JOUVET, E. DELAIS-ROUSSARIE.*Prosodic Parameters and Prosodic Structures of French Emotional Data*, in "Speech Prosody 2016", Boston, United States, Speech Prosody 2016, May 2016, https://hal.inria.fr/hal-01293516.

[24] N. BERTIN, E. CAMBERLEIN, E. VINCENT, R. LEBARBENCHON, S. PEILLON, É. LAMANDÉ, S. SIVASANKARAN, F. BIMBOT, I. ILLINA, A. TOM, S. FLEURY, E. JAMET.*A French corpus for distant-microphone speech processing in real homes*, in "Interspeech 2016", San Francisco, United States, September 2016, https://hal.inria.fr/hal-01343060.

[25] M. CADOT, A. BONNEAU.*Du fichier audio à l'intonation en Français :Graphes pour l'apprentissage de 3 classes intonatives*, in "Fouille de données complexes (FDC@EGC2016)", Reims, France, Proceedings of FDC@EGC2016, January 2016, https://hal.archives-ouvertes.fr/hal-01292121.

[26] A. CURREY, I. ILLINA, D. FOHR.*Dynamic adjustment of language models for automatic speech recognition using word similarity* , in "IEEE Workshop on Spoken Language Technology (SLT 2016)", San Diego, CA, United States, proceeding of IEEE Workshop on Spoken Language Technology, December 2016, https://hal.archives-ouvertes.fr/hal-01384365.

[27] K. DÉGUERNEL, E. VINCENT, G. ASSAYAG.*Using Multidimensional Sequences For Improvisation In The OMax Paradigm*, in "13th Sound and Music Computing Conference", Hamburg, Germany, August 2016, https://hal.inria.fr/hal-01346797.

[28] B. ELIE, G. CHARDON.*Robust tonal and noise separation in presence of colored noise, and application to voiced fricatives*, in "22nd International Congress on Acoustics (ICA)", Buenos Aires, Argentina, September 2016, https://hal.archives-ouvertes.fr/hal-01372313.

[29] B. ELIE, Y. LAPRIE.*A glottal chink model for the synthesis of voiced fricatives*, in "International Conference on Acoustics, Speech and Signal Processing (ICASSP)", Shanghai, China, IEEE, March 2016, https://hal.archives-ouvertes.fr/hal-01314308.

[30] B. ELIE, Y. LAPRIE.*Copy synthesis of phrase-level utterances*, in "EUSIPCO2016", Budapest, Hungary, August 2016, https://hal.archives-ouvertes.fr/hal-01278462.

[31] B. ELIE, Y. LAPRIE.*Copy synthesis of running speech based on vocal tract imaging and audio recording*, in "22nd International Congress on Acoustics (ICA)", Buenos Aires, Argentina, September 2016, https://hal.archives-ouvertes.fr/hal-01372310.

[32] B. ELIE, Y. LAPRIE, P.-A. VUISSOZ, F. ODILLE.*High spatiotemporal cineMRI films using compressed sensing for acquiring articulatory data*, in "EUSIPCO2016", Budapest, Hungary, August 2016, https://hal.archives-ouvertes.fr/hal-01372320.

[33] B. ELIZALDE, A. KUMAR, A. SHAH, R. BADLANI, E. VINCENT, B. RAJ, I. LANE.*Experiments on the DCASE Challenge 2016: Acoustic scene classification and sound event detection in real life recording*, in "DCASE2016 Workshop on Detection and Classification of Acoustic Scenes and Events", Budapest, Hungary, September 2016, https://hal.inria.fr/hal-01354007.

[34] D. FITZGERALD, A. LIUTKUS, R. BADEAU.*PROJET - Spatial Audio Separation Using Projections*, in "41st International Conference on Acoustics, Speech and Signal Processing (ICASSP)", Shanghai, China, IEEE, 2016, https://hal.archives-ouvertes.fr/hal-01248014.

[35] M. FONTAINE, C. VANWYNSBERGHE, A. LIUTKUS, R. BADEAU.*Sketching for nearfield acoustic imaging of heavy-tailed sources*, in "13th International Conference on Latent Variable Analysis and Signal Separation (LVA/ICA 2017)", Grenoble, France, Proc. 13th International Conference on Latent Variable Analysis and Signal Separation (LVA/ICA 2017), February 2017, https://hal.archives-ouvertes.fr/hal-01401988.

[36] S. GHOSH, C. FAUTH, A. SINI, Y. LAPRIE.*L1-L2 Interference: The case of final devoicing of French voiced fricatives in final position by German learners*, in "Interspeech 2016", San Francisco, United States,

September 2016, vol. 2016, p. 3156 - 3160 [*DOI :* 10.21437/INTERSPEECH.2016-954], https://hal.inria.fr/hal-01397176.

[37] S. LEGLAIVE, U. SIMSEKLI, A. LIUTKUS, R. BADEAU, G. RICHARD.*Alpha-Stable Multichannel Audio Source Separation*, in "42nd International Conference on Acoustics, Speech and Signal Processing (ICASSP)", New Orleans, United States, Proc. 42nd International Conference on Acoustics, Speech and Signal Processing (ICASSP), IEEE, March 2017, https://hal.archives-ouvertes.fr/hal-01416366.

[38] V. Q. NGUYEN, F. COLAS, E. VINCENT, F. CHARPILLET.*Localizing an Intermittent and Moving Sound Source Using a Mobile Robot*, in "International Conference on Intelligent Robots and Systems (IROS)", Deajeon, South Korea, October 2016, https://hal.archives-ouvertes.fr/hal-01354006.

[39] A. A. NUGRAHA, A. LIUTKUS, E. VINCENT.*Multichannel music separation with deep neural networks*, in "European Signal Processing Conference (EUSIPCO)", Budapest, Hungary, Proceedings of the 24th European Signal Processing Conference (EUSIPCO), August 2016, p. 1748-1752, https://hal.inria.fr/hal-01334614.

[40] S. OUNI, V. COLOTTE, S. DAHMANI, S. AZZI.*Acoustic and Visual Analysis of Expressive Speech: A Case Study of French Acted Speech*, in "Interspeech 2016", San Francisco, United States, ISCA, November 2016, vol. 2016, p. 580 - 584 [*DOI :* 10.21437/INTERSPEECH.2016-730], https://hal.inria.fr/hal-01398528.

[41] A. PIQUARD-KIPFFER.*Storytelling with a digital album that use an avatar as narrator*, in "XVIèmes rencontres internationales en orthophonie - Orthophonie et technologies innovantes", PARIS, France, XVIèmes rencontres internationales en orthophonie - Orthophonie et technologies innovantes, December 2016, https://hal.inria.fr/hal-01403204.

[42] D. RIBAS, E. VINCENT, J. R. CALVO.*A study of speech distortion conditions in real scenarios for speech processing applications*, in "2016 IEEE Workshop on Spoken Language Technology", San Diego, United States, December 2016, https://hal.inria.fr/hal-01377638.

[43] G. SERRIÈRE, C. CERISARA, D. FOHR, O. MELLA.*Weakly-supervised text-to-speech alignment confidence measure*, in "International Conference on Computational Linguistics (COLING)", Osaka, Japan, Proceedings of the 26th International Conference on Computational Linguistics (COLING), December 2016, https://hal.archives-ouvertes.fr/hal-01378355.

[44] I. SHEIKH, I. ILLINA, D. FOHR, G. LINARES.*Document Level Semantic Context for Retrieving OOV Proper Names*, in "2016 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)", shanghai, China, Proceeding of IEEE ICASSP 2016, IEEE, March 2016, p. 6050-6054 [*DOI :* 10.1109/ICASSP.2016.7472839], https://hal.archives-ouvertes.fr/hal-01331716.

[45] I. SHEIKH, I. ILLINA, D. FOHR, G. LINARES.*Improved Neural Bag-of-Words Model to Retrieve Out-of-Vocabulary Words in Speech Recognition*, in "INTERSPEECH 2016", San Francisco, United States, Proceedings of INTERSPEECH 2016, September 2016, vol. 2016 [*DOI :* 10.21437/INTERSPEECH.2016-1219], https://hal.archives-ouvertes.fr/hal-01384488.

[46] I. SHEIKH, I. ILLINA, D. FOHR, G. LINARES.*Learning Word Importance with the Neural Bag-of-Words Model*, in "ACL, Representation Learning for NLP (Repl4NLP) workshop", Berlin, Germany, Proceedings of ACL 2016, August 2016, https://hal.archives-ouvertes.fr/hal-01331720.

[47] I. SHEIKH, I. ILLINA, D. FOHR.*How Diachronic Text Corpora Affect Context based Retrieval of OOV Proper Names for Audio News*, in "LREC 2016", Portoroz, Slovenia, proceedings of LREC 2016, May 2016, https://hal.archives-ouvertes.fr/hal-01331714.

[48] A. J. R. SIMPSON, G. ROMA, E. M. GRAIS, R. D. MASON, C. HUMMERSONE, A. LIUTKUS, M. D. PLUMBLEY.*Evaluation of Audio Source Separation Models Using Hypothesis-Driven Non-Parametric Statistical Methods*, in "European Signal Processing Conference", Budapest, Hungary, EURASIP, August 2016, https://hal.inria.fr/hal-01410176.

[49] S. SIVASANKARAN, E. VINCENT, I. ILLINA.*Discriminative importance weighting of augmented training data for acoustic model training*, in "42th International Conference on Acoustics, Speech, and Signal Processing (ICASSP 2017)", New Orleans, United States, March 2017, https://hal.inria.fr/hal-01415759.

[50] F.-R. STÖTER, A. LIUTKUS, R. BADEAU, B. EDLER, P. MAGRON.*Common Fate Model for Unison source Separation*, in "41st International Conference on Acoustics, Speech and Signal Processing (ICASSP)", Shanghai, China, Proceedings of the 41st International Conference on Acoustics, Speech and Signal Processing (ICASSP), IEEE, 2016, https://hal.archives-ouvertes.fr/hal-01248012.

[51] J. TROUVAIN, A. BONNEAU, V. COLOTTE, C. FAUTH, D. FOHR, D. JOUVET, J. JÜGLER, Y. LAPRIE, O. MELLA, B. MÖBIUS, F. ZIMMERER.*The IFCASL Corpus of French and German Non-native and Native Read Speech*, in "LREC'2016, 10th edition of the Language Resources and Evaluation Conference", Portorož, Slovenia, Proceedings LREC'2016, May 2016, https://hal.inria.fr/hal-01293935.

[52] F. ZIMMERER, A. BONNEAU, B. ANDREEVA.*Influence of L1 prominence on L2 production: French and German speakers*, in "Speech Prosody 2016", Boston, United States, May 2016, vol. 2016, p. 370 - 374 [*DOI :* 10.21437/SPEECHPROSODY.2016-76], https://hal.inria.fr/hal-01399974.

National Conferences with Proceeding

[53] B. ELIE, Y. LAPRIE, P.-A. VUISSOZ.*Acquisition temps-réel de données articulatoires par IRM : application à la synthèse par copie*, in "13ème Congrès Français d'Acoustique (CFA 2016)", Le Mans, France, SFA, April 2016, https://hal.archives-ouvertes.fr/hal-01314313.

Conferences without Proceedings

[54] F. ZIMMERER, J. TROUVAIN, A. BONNEAU.*Methods of investigating vowel interferences of French learners of German*, in "New Sounds 2016", Aarhus, Denmark, June 2016, https://hal.inria.fr/hal-01400005.

Scientific Books (or Scientific Book chapters)

[55] J. BARKER, R. MARXER, E. VINCENT, S. WATANABE.*The CHiME challenges: Robust speech recognition in everyday environments*, in "New era for robust speech recognition - Exploiting deep learning", Springer, October 2016, https://hal.inria.fr/hal-01383263.

[56] M. CADOT.*Recoder les variables pour obtenir un modèle implicatif optimal*, in "L'Analyse Statisqtique Implicative", R. GRAS (editor), Cépaduès, December 2016, https://hal.archives-ouvertes.fr/hal-01398229.

Research Reports

[57] P. MAGRON, R. BADEAU, A. LIUTKUS.*Generalized Wiener filtering for positive alpha-stable random variables*, Télécom ParisTech, June 2016, https://hal.archives-ouvertes.fr/hal-01340797.

[58] G. SARGENT, F. BIMBOT, E. VINCENT.*Supplementary material to the article: Estimating the structural segmentation of popular music pieces under regularity constraints*, IRISA-Inria, Campus de Beaulieu, 35042 Rennes cedex ; Inria Nancy, équipe Multispeech, September 2016, https://hal.inria.fr/hal-01368683.

Scientific Popularization

[59] A. LIUTKUS, E. VINCENT.*Démixer la musique*, in "Interstices", January 2016, https://hal.inria.fr/hal-01350450.

[60] A. PIQUARD-KIPFFER.*Faire voir une histoire : Louis et son incroyable chien Noisette*, in "Les Cahiers Pédagogiques", February 2016, vol. Hors série numérique N°42, 7, https://hal.inria.fr/hal-01191878.

Patents and standards

[61] S. OUNI, G. GRIS.*Dispositif de traitement d'image*, January 2016, n^{o} 15 52058, Le rapport de recherche reconnait la brevetabilité, https://hal.inria.fr/hal-01294028.

Other Publications

[62] B. DUMORTIER, E. VINCENT, M. DEACONU, P. CORNU.*Efficient optimisation of wind power under acoustic constraints*, November 2016, working paper or preprint, https://hal.inria.fr/hal-01393125.

[63] B. ELIE, Y. LAPRIE.*Acoustic impact of the glottal chink on the production of fricatives: A numerical study*, December 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01423206.

[64] A. PIQUARD-KIPFFER, T. LÉONOVA.*Parcours scolaire de 166 dysphasiques et/ou dyslexiques-dysorthographiques âgés de 6 à 20 ans en situation de handicap : Schooling experiences of 166 dysphasic or dyslexics-dysorthographic children, aged from 6 to 20 in a handicap situation*, July 2016, working paper or preprint, https://hal.inria.fr/hal-01402986.

[65] A. PIQUARD-KIPFFER, O. MELLA, J. MIRANDA, D. JOUVET, L. OROSANU.*Terminal portable de communication et affichage de la reconnaissance vocale. Enjeux et rapports à l'écrit. Étude préliminaire auprès d'adultes déficients auditifs*, March 2016, 15p., In M.Frisch (Eds) Le réseau Idéki : Didactiques, métiers de l'humain et Intelligence collective. Nouveaux espaces et dispositifs en question. Nouveaux horizons en éducation, formation et en recherche. L'harmattan, Collection I.D, https://hal.inria.fr/hal-01239910.

References in notes

[66] A. LIUTKUS, R. BADEAU.*Generalized Wiener filtering with fractional power spectrograms*, in "2015 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)", IEEE, 2015, p. 266–270.

Project-Team NEUROSYS

Analysis and modeling of neural systems by a system neuroscience approach

IN COLLABORATION WITH: Laboratoire lorrain de recherche en informatique et ses applications (LORIA)

IN PARTNERSHIP WITH:
CNRS

Université de Lorraine

RESEARCH CENTER
Nancy - Grand Est

THEME
Computational Neuroscience and Medecine

Table of contents

Project-Team NEUROSYS

Creation of the Team: 2013 January 01, updated into Project-Team: 2015 July 01

Keywords:

Computer Science and Digital Science:

3.3. - Data and knowledge analysis
3.4. - Machine learning and statistics
5.1.4. - Brain-computer interfaces, physiological computing
5.9.2. - Estimation, modeling
5.11.1. - Human activity analysis and recognition
6.1.1. - Continuous Modeling (PDE, ODE)
6.1.2. - Stochastic Modeling (SPDE, SDE)
6.1.4. - Multiscale modeling
6.3.4. - Model reduction
8.2. - Machine learning
8.3. - Signal analysis

Other Research Topics and Application Domains:

1.3. - Neuroscience and cognitive science
1.3.1. - Understanding and simulation of the brain and the nervous system
1.3.2. - Cognitive science
1.4. - Pathologies
2.2.2. - Nervous system and endocrinology
2.5.1. - Sensorimotor disabilities

1. Members

Research Scientist

Axel Hutt [Inria, Senior Researcher, secondment at Deutscher Wetterdienst, HDR]

Faculty Members

Laurent Bougrain [Team leader, Univ. Lorraine, Associate Professor]
Laure Buhry [Univ. Lorraine, Associate Professor]
Tamara Tošić [Univ. Lorraine, Temporary Associate Professor]

PhD Students

Amélie Aussel [Univ. Lorraine, from Oct. 2016]
Mariia Fedotenkova [Inria]
Francesco Giovannini [Inria]
Cecilia Lindig-Leòn [Inria]
Sébastien Rimbert [Inria]
Meysam Hashemi [Inria, until Jan. 2016]

Administrative Assistants

Laurence Benini [Inria, until Jul. 2016]
Isabelle Herlich [Inria, from Aug. 2016]
Laurence Félicité [Univ. Lorraine]
Christelle Lévèque [Univ. Lorraine]

Others

Kanishka Basnayake [CNRS, Intern, until Jul. 2016]
Yann Bernard [Inria, Intern, from Apr. 2016 until Jun. 2016]
Constant Denis [Univ. Lorraine, Intern, until Jul. 2016]
Jimmy Nex [Inria, Intern, until Jul. 2016]
Louis Viard [Inria, Intern, until Sep. 2016]

2. Overall Objectives

2.1. General Objectives

The team aims at understanding the dynamics of neural systems on multiple scales and develops methods to invent monitoring devices. The approach is inspired by systems neuroscience, which relates microscopic modifications in neural systems to macroscopic changes in behavior. The team employs this systems neuroscience approach and develops models and data analysis tools in order to bridge the gap between microscopic and mesoscopic, and mesoscopic and macroscopic/behavior activity. These bridges are necessary to better understand neural systems and, in turn, control the neural systems. They also may allow to develop data monitors utilising the derived principles. As a long-term goal, the team shall develop such devices in medicine with application in general anaesthesia.

3. Research Program

3.1. Main Objectives

The main challenge in computational neuroscience is the high complexity of neural systems. The brain is a complex system and exhibits a hierarchy of interacting subunits. On a specific hierarchical level, such subunits evolve on a certain temporal and spatial scale. The interactions of small units on a low hierarchical level build up larger units on a higher hierarchical level evolving on a slower time scale and larger spatial scale. By virtue of the different dynamics on each hierarchical level, until today the corresponding mathematical models and data analysis techniques on each level are still distinct. Only few analysis and modeling frameworks are known which link successfully at least two hierarchical levels.

Once having extracted models for different description levels, typically they are applied to obtain simulated activity which is supposed to reconstruct features in experimental data. Although this approach appears straightforward, it presents various difficulties. Usually the models involve a large set of unknown parameters which determine the dynamical properties of the models. To optimally reconstruct experimental features, it is necessary to formulate an inverse problem to extract optimally such model parameters from the experimental data. Typically this is a rather difficult problem due to the low signal-to-noise ratio in experimental brain signals. Moreover, the identification of signal features to be reconstructed by the model is not obvious in most applications. Consequently an extended analysis of the experimental data is necessary to identify the interesting data features. It is important to combine such a data analysis step with the parameter extraction procedure to achieve optimal results. Such a procedure depends on the properties of the experimental data and hence has to be developed for each application separately. Machine learning approaches that attempt to mimic the brain and its cognitive processes had a lot of success in classification problems during the last decade. These hierarchical and iterative approaches use non-linear functions, which imitate neural cell responses, to communicate messages between neighboring layers. In our team, we work towards developing polysomnography-specific classifiers that might help in linking the features of particular interest for building systems for sleep signal classification with sleep mechanisms, with the accent on memory consolidation during the Rapid Eye Movement (REM) sleep phase.

3.2. Challenges

Eventually the implementation of the models and analysis techniques achieved promises to be able to construct novel data monitors. This construction involves additional challenges and stipulates the contact to realistic environments. By virtue of the specific applications of the research, the close contact to hospitals and medical enterprises shall be established in a longer term in order to (i) gain deeper insight into the specific application of the devices and (ii) build specific devices in accordance to the actual need. Collaborations with local and national hospitals and the pharmaceutical industry already exist.

3.3. Research Directions

- From the microscopic to the mesoscopic scale:
  One research direction focuses on the *relation of single neuron activity* on the microscopic scale *to the activity of neuronal populations*. To this end, the team investigates the stochastic dynamics of single neurons subject to external random inputs and involving random microscopic properties, such as random synaptic strengths and probability distributions of spatial locations of membrane ion channels. Such an approach yields a stochastic model of single neurons and allows the derivation of a stochastic neural population model.

  This bridge between the microscopic and mesoscopic scale may be performed via two pathways. The analytical and numerical treatment of the microscopic model may be called a *bottom-up approach*, since it leads to a population activity model based on microscopic activity. This approach allows theoretical neural population activity to be compared to experimentally obtained population activity. The *top-down approach* aims at extracting signal features from experimental data gained from neural populations which give insight into the dynamics of neural populations and the underlying microscopic activity. The work on both approaches represents a well-balanced investigation of the neural system based on the systems properties.
- From the mesoscopic to the macroscopic scale:
  The other research direction aims to link neural population dynamics to macroscopic activity and behaviour or, more generally, to phenomenological features. This link is more indirect but a very powerful approach to understand the brain, e.g., in the context of medical applications. Since real neural systems, such as in mammals, exhibit an interconnected network of neural populations, the team studies analytically and numerically the network dynamics of neural populations to gain deeper insight into possible phenomena, such as traveling waves or enhancement and diminution of certain neural rhythms. Electroencephalography (EEG) is a wonderful brain imaging technique to study the overall brain activity in real time non-invasively. However it is necessary to develop robust techniques based on stable features by investigating the time and frequency domains of brain signals. Two types of information are typically used in EEG signals: (i) transient events such as evoked potentials, spindles and K-complexes and (ii) the power in specific frequency bands.

4. Application Domains

4.1. General remarks

The research directions of the team are motivated by general anaesthesia (GA) that has attracted our attention in the last years. The following paragraphs explain in some detail the motivation of our work on the four major phenomena of GA: loss of consciousness, immobility, amnesia and analgesia.

During general anaesthesia, the electroencephalogram (EEG) on the scalp changes characteristically: increasing the anaesthetic drug concentration the amplitudes of oscillations in the α-band ($\sim 8-12$Hz) and in the $\delta-$band ($2-8$Hz) increase amplitudes in frontal electrodes at low drug concentrations whereas the spectral power decreases in the $\gamma-$band ($\sim 20-60$Hz). This characteristic change in the power is the basis of today's EEG-monitors that assist the anaesthetist in the control of the anaesthesia depths of patients during surgery. However, the conventional monitors exhibit a large variability between the detected anaesthetic depth and the real depth of patients. Moreover, a certain number of patients re-gain consciousness during surgery (about $1-2$ out of 1000) and a large percentage of patients suffer from diverse after-effects, such as nausea or long-lasting cognitive impairments such as partial amnesia (from days to weeks). Since surgery under general anaesthesia is part of a hospital's everyday practice, a large number of patients suffer from these events every day. One reason for the lacking control of such disadvantageous effects is the dramatic lack of knowledge on what is going on in the brain during general anaesthesia and a weak EEG-online monitoring system during anaesthesia. Consequently, to improve the situation of patients during and after surgery and to develop improved anaesthetic procedures or even drugs, research is necessary to learn more about the neural processes in the brain and develop new monitoring machines.

4.2. Level of consciousness

The EEG originates from coherent neural activity of populations in the cortex. Hence to understand better the characteristic power changes in EEG during anaesthesia, it is necessary to study neural population dynamics subject to the concentration of anaesthetic drugs and their action on receptors on the single neuron level. We study mathematical models which will be constrained by the signal features extracted from experimental data, such as EEG (data provided by Jamie Sleigh, University of Auckland and Christoph Destrieux, University of Tours), Local Field Potentials (data provided by Flavio Fröhlich, University of North Carolina - Chapel Hill) and behavior. The combination of model and analysis of experimental data provides the optimal framework to reveal new knowledge on the neural origin of behavioral features, such as the loss of consciousness or the uncontrolled gain of consciousness during surgery. For instance, modelling studies show that the characteristic changes of spectral power (second-order statistics) are not sufficient to deduce all underlying neural mechanisms. Consequently, additional higher-order statistical measures may provide additional insight into underlying neural mechanisms and may provide a novel marker for the loss of consciousness.

Moreover, the constant supervision of anesthetized patients in intensive care is a demanding task for the personnel in hospital practice. It is almost not possible to take care of a patient constantly and hence the todays' medicine demands monitoring devices that control automatically the level of anaesthetic drugs based on the patients' neural activity (e.g., EEG). Brain-Computer-Interfaces (BCI) have already demonstrated their potential for the detection of consciousness in non-responsive patients. We will apply the data analysis techniques known in BCI to extract new markers for the depth of anaesthesia. More specifically, for deeper anaesthesia, auditory-evoked and Event-Related Desynchronization/Event-Related Synchronization (ERD/ERS) BCI could be used to better identify the state of consciousness in patients under anaesthesia. In this context, we have established a first contact to the University of Würzburg. Another research direction will link intracranial EEG and scalp EEG by characterising micro-awake episodes during sleep.

4.3. Immobility

A research direction will be to take benefit of the relationship between the motor activity and anesthesia. Indeed, even if no movement is visually perceptible, a study by electroencephalographic recordings of brain activity in motor areas, quantifying the characteristics of amplitude and phase synchronization observed in the alpha and beta frequency bands, may reveal an intention of movement. This feature is important because it demonstrates that the patient is aware. Thus, we will develop an experimental protocol in collaboration with an anesthesiologist of the regional hospital on stimulating the median nerve at forearm level to track the evolution of the shape of the beta rebound in the motor cortex for various doses of the anesthetic agent.

4.4. Amnesia

Patients sometimes develop post-traumatic disorders associated with the surgery they underwent because they either woke up during the surgery or because the amnesiant effect of the general anaesthesia was only partial, declarative memory being maintained in some unexplained cases. It is still unknown how memory can be maintained under general anaesthesia and it needs to be investigated to improve the recovery from anaesthesia and to avoid as much as possible post-traumatic disorders. To learn more about memory under anaesthesia, we will focus our theoretical studies on the oscillation regimes observed in the hippocampus, mainly in the theta and gamma ranges, which are correlated with memory formation and retrieval.

4.5. Analgesia

One of the most important aspect in general anaesthesia is the loss of pain. During surgery, it is very difficult to find out whether the anesthetized patient feels pain and hence will develop cognitive impairment after surgery. Today, the anesthesiologist knows and detects physiological signs of pain, such as sweat, colour of skin or spontaneous involuntary movements. However, more objective criteria based on EEG may assist the pain detection and hence improves the patients' situation. To this end, we analyze large sets of patient EEG-data observed during surgery and aim to extract EEG signal features of pain.

5. Highlights of the Year

5.1. Highlights of the Year

- Laurent Bougrain has co-supervised and co-written a two-volume book for anyone who uses Brain-Computer Interfaces, in English [17], [18] and for the first time in French [19], [20]. The multidisciplinary work has involved around fifty authors from various backgrounds, who write about their particular area of expertise in a way that makes it accessible to a wider audience. That includes healthcare professionals, video game developers, researchers and students, as well as a much wider audience, curious to explore the philosophical and ethical aspects of this subject. The book also has a practical side, with tutorials illustrating the use of BCI and the OpenViBE software platform (see 6.6 and http://openvibe.inria.fr). Laurent Bougrain contributed to several chapters about the state of the art, medical applications and OpenViBE [15], [10], [12], [13] (French version: [16], [9], [11], [14]).
- We stepped up our collaboration with the *department of neurology of the university hospital in Nancy* (Louise Tyvaert, Louis Maillard, Laurent Koessler) leading to i) a **project PEPS JCJC** on modeling and simulation of the oscillatory activity of the memory system during sleep and under general anesthesia (see section 9.2) a **PhD thesis** started in October 2016 (Amélie Aussel), funded by UL and co-supervised by Laure Buhry (Loria-Neurosys) and Radu Ranta (CRAN). This thesis will make use of SEEG recordings made in epileptic patients and will use preliminary results on hippocampal modelling obtained thanks to the project PEPS JCJC.

6. New Software and Platforms

6.1. AnaesthesiaSimulator

KEYWORDS: General anaesthesia - Spiking neural networks - Health
FUNCTIONAL DESCRIPTION

AnaesthesiaSimulator simulates the activity of networks of spiking neurons subject to specific receptor dynamics. The tool is a platform to test effects of anaesthetics on neural activity and is still in its first stage of development. The neural activity is planned to be visualized in a 2D and 3D-plot evolving in time. It is written in Python, open-source and involves heavily the simulation package BRIAN.

- Participants: Axel Hutt and Laure Buhry
- Partner: University of Auckland
- Contact: Axel Hutt
- URL: https://gforge.inria.fr/projects/anasim/

6.2. BrianModel

Library of Brian Neuron Models
KEYWORDS: Spiking neural networks - Neurosciences - Numerical simulations
FUNCTIONAL DESCRIPTION

BrianModel is a library of neuron models and ionic currents for the BRIAN simulator. The purpose of BrianModel is to speed up simulation set-up and reduce code duplication across simulation scripts. Template neurons are defined by the ionic currents that flow through their membrane. Implemented templates include: Hodgkin-Huxley pyramidal neuron, Hodgkin-Huxley pyramidal neuron with CAN receptors, Hodgkin-Huxley fast-spiking inhibitory hippocampal. The current library is easily extensible by third-party users due to its hierarchical design. The template neurons and their currents are defined as YAML files, which are conveniently parsed by a Python library which acts as an interface to the BRIAN simulator API's.

- Contact: Francesco Giovannini
- URL: https://github.com/JoErNanO/brianmodel

6.3. MATCWT

continuous wavelet transform
KEYWORDS: Matlab - Visualization - Signal processing
FUNCTIONAL DESCRIPTION

This MATLAB script builds continuous wavelet transform (CWT) allowing to choose scales/frequencies and how to compute cone of influence (COI). It uses built-in MATLAB functions to calculate the transform (cwt.m and cwtft.m). This function returns scalogram, percentage energy for each coefficient of CWT. It also plots CWT (if such option is specified), all the values on the plot are linear ones. Plot function displays COI as hatched regions, to do so an additional function is required. Hatchfill function was used for that. I modifies this function slightly in order to control color of hatch lines and added to the repo for convenience. Otherwise, instead of using hatched regions, COI can be indicated by using MATLAB patch function with alpha set to a value less than 1.

- Contact: Mariia Fedotenkova
- URL: https://github.com/mfedoten/wavelets

6.4. MATSPECTRO

Spectrogram reassignment
KEYWORDS: Matlab - Visualization - Signal processing
FUNCTIONAL DESCRIPTION

This matlab function computes reassigned version of the conventional and multitaper spectrograms. The algorithm is based on Auger and Flandrin method, some parts are adopted from Fulop and Fitz. The idea is to first compute conventional spectrogram, then find optimal (in a sense of energy) time and frequency positions and reassigns values in the spectrogram to this new positions. The difference between conventional and multitaper spectrograms is that multitaper method computes additional spectrogram with each taper. Taper is a generic term for a window function but in this method tapers refer to Slepian sequences. As a result, generally multitaper spectrogram reveals less variance than conventional one.

- Contact: Mariia Fedotenkova
- URL: https://github.com/mfedoten/reasspectro

6.5. NFSimulator

NeuralFieldSimulator
KEYWORDS: Neurosciences - Simulation - Health
FUNCTIONAL DESCRIPTION

The NeuralFieldSimulator computes numerically activity in two-dimensional neural fields by solving integral-differential equations involving transmission delays and visualizes the spatio-temporal activity. The tool includes a GUI that allows the user to choose field parameters. It is written in Python, open-source and is aimed to be promoted to become a major graphical visualization tool in the domain of neural field theory. We aim to establish this simulation software as the first open-source standard simulator for the neural field research community.

- Contact: Axel Hutt
- URL: https://gforge.inria.fr/projects/nfsimulator/

6.6. OpenVIBE

KEYWORDS: Neurosciences - Interaction - Virtual reality - Health - Real time - Neurofeedback - Brain-Computer Interface - EEG - 3D interaction
FUNCTIONAL DESCRIPTION

OpenViBE is a software platform for real-time neurosciences (that is, for real-time processing of brain signals). It can be used to acquire, filter, process, classify and visualize brain signals in real time from various signal sources. OpenViBE is free and open source software. It works on Windows and Linux operating systems.

- Participants: Yann Renard, Anatole Lécuyer, Fabien Lotte, Bruno Renier, Vincent Delannoy, Laurent Bonnet, Baptiste Payan, Jozef Legény, Jussi Tapio Lindgren, Alison Cellard, Loïc Mahé, Guillaume Serriere, Marsel Mano, Maureen Clerc Gallagher, Théodore Papadopoulo, Laurent Bougrain, Jérémy Frey and Nathanaël Foy
- Partners: CEA-List - GIPSA-Lab - INSERM
- Contact: Anatole Lécuyer, Hybrid/Inria Rennes-Bretagne Atlantique
- URL: http://openvibe.inria.fr

6.7. Platforms

6.7.1. EEG experimental room

A room at Inria Nancy - Grand Est is now dedicated to electroencephalographic recordings. An umbrella agreement and several additional experiment descriptions have been approved by the Inria Operational Legal and Ethical Risk Assessment Committee (COERLE).

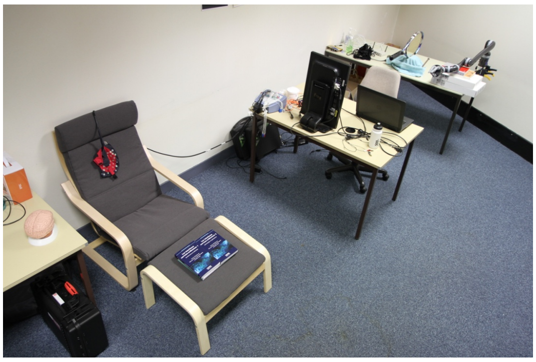

Figure 1. Electroencephalographic Experimental room at Inria Nancy-Grand Est

7. New Results

7.1. From the microscopic to the mesoscopic scale

Participants: Laure Buhry, Francesco Giovannini
In collaboration with Beate Knauer and Motoharu Yoshida (Ruhr University) and LieJune Shiau (University of Houston)

7.1.1. Memory and Anaesthesia

7.1.1.1. The CAN-In model of hippocampal theta oscillations

During working memory tasks, the hippocampus exhibits synchronous theta-band activity, which is thought to be correlated with the short-term memory maintenance of salient stimuli. Recent studies indicate that the hippocampus contains the necessary circuitry allowing it to generate and sustain theta oscillations without the need of extrinsic drive. However, the cellular and network mechanisms supporting synchronous rhythmic activity are far from being fully understood. Based on electrophysiological recordings from hippocampal pyramidal CA1 cells, we have presented a possible mechanism for the maintenance of such rhythmic theta-band activity in the isolated hippocampus [3]. Our model network, based on the Hodgkin-Huxley formalism, comprising pyramidal neurons equipped with calcium-activated non-specific cationic (CAN) ion channels, is able to generate and maintain synchronized theta oscillations ($4-12\,Hz$), following a transient stimulation. The synchronous network activity is maintained by an intrinsic CAN current (I_{CAN}), in the absence of constant external input. The analysis of the dynamics of model networks of pyramidal-CAN and interneurons (CAN-In) reveals that feedback inhibition improves the robustness of fast theta oscillations, by tightening the synchronisation of the pyramidal CAN neurons. The frequency and power of the theta oscillations are both modulated by the intensity of the I_{CAN}, which allows for a wide range of oscillation rates within the theta band.

This biologically plausible mechanism for the maintenance of synchronous theta oscillations in the hippocampus aims at extending the traditional models of septum-driven hippocampal rhythmic activity.

7.1.1.2. Generation of gamma oscillations in a network of adaptive exponential integrate and fire neurons

Fast neuronal oscillations in the Gamma rhythm (20-80 Hz) are observed in the neocortex and hippocampus during behavioral arousal. Through a conductance-based, four-dimensional Hodgkin-Huxley type neuronal model, Wang and Buzsáki have numerically demonstrated that such rhythmic activity can emerge from a random network of GABAergic interneurons when their intrinsic neuronal characters and network structure act as the main drive of the rhythm. We investigate Gamma oscillations through a randomly connected network model comprising low complexity, two-dimensional adaptive exponential integrate-and-fire (AdEx) neurons that have subthreshold and spike-triggered adaptation mechanisms. Despite the simplicity of our network model, it shares two important results with the previous biophysical model: the minimal number of necessary synaptic inputs to generate coherent Gamma-band rhythms remains the same, and this number is weakly-dependant on the network size. Using AdEx model, we also investigate the necessary neuronal, synaptic and connectivity properties that lead to random network synchrony with Gamma rhythms. These findings suggest a computationally more tractable framework for studying sparse and random networks inducing cortical rhythms in the Gamma band (Laure Buhry submitted an article to Journal of Computational Neuroscience, currently under major revision).

7.2. From the Mesoscopic to the Macroscopic Scale

Participants: Laurent Bougrain, Axel Hutt, Tamara Tošić, Mariia Fedotenkova, Meysam Hashemi, Cecilia Lindig-Leon, Jimmy, Nex, Sébastien Rimbert.
In collaboration with Stéphanie Fleck (Univ. Lorraine), Nathalie Gayraud (Inria Sophia Antipolis) and Maureen Clerc (Inria Sophia Antipolis)

7.2.1. Level of Consciousness

Participants: Axel Hutt, Meysam Hashemi
Meysam Hashemi defended his thesis about analytical and numerical studies of thalamo-cortical neural population models during general anesthesia. The findings of this thesis provide new insights into the mechanisms responsible for the specific changes in EEG patterns that are observed during propofol-induced sedation. Our results indicate that depending on the mean potential values of the system resting states, an increase or decrease in the thalamo-cortical gain functions results in an increase or decrease in the alpha power, respectively. In contrast, the evolution of the delta power is rather independent of the system resting states; the enhancement of spectral power in delta band results from the increased synaptic or extra-synaptic GABAergic inhibition. Furthermore, we aim to identify the parameters of a thalamo-cortical model by fitting the model power spectrum to the EEG recordings. To this end, we address the task of parameter estimation in the models that are described by a set of stochastic ordinary or delay differential equations [2].

7.2.2. Motor system

Participants: Laurent Bougrain, Cecilia Lindig-Leon, Jimmy, Nex, Sébastien Rimbert.
In collaboration with Stéphanie Fleck (Univ. Lorraine), Nathalie Gayraud (Inria Sophia Antipolis) and Maureen Clerc (Inria Sophia Antipolis)

7.2.2.1. Incremental motor imagery learning for rehabilitation after stroke

After a stroke, Brain-Computer Interfaces (BCI) allows improving rehabilitation of the motor cortex to recover the autonomy of the patient. The design of BCIs has to be done with an in-depth analysis concerning user's conditions during the learning of BCI. Since strokes affect mainly senior citizens, it is very important to guide the design of BCIs to make it usable. We propose to improve the experimental conditions through a new BCI protocol including an incremental motor imagery learning [21].

7.2.2.2. Motor neuroprostheses

We wrote a review that aims to position current neuroprosthetics research between reality and fiction, expectations of persons under a disability, fantasies of the augmented Man and scientific difficulties. Beyond the buzz effect to get the attention of the public and funders, and enthusiasm by journalists for novelty what are the expectations of potential users, the disappointments and the satisfactions of patients, how many persons are equipped, what are the price and the opportunities to use such devices outside of laboratories [5].

7.2.2.3. Classification of Motor patterns

In order to build systems that are able to detect several motor patterns, multiclass schemes need to be applied. We compared a series of multiclass approaches to assert the benefits of hierarchical classification. The compared methods are based on two effective techniques for MI-discrimination, namely, Common Spatial Patterns (CSP) and Riemannian geometry, for which the hierarchical and non-hierarchical approaches have been considered. We include the CSP by Joint Diagonalization method, which corresponds with a non-hierarchical approach; and its hierarchical counterpart, namely, Binary CSP. In addition, the non-hierarchical Minimum Distance to Riemannian Mean method (MDRM) is also evaluated, together with its analogous hierarchical approach; a contribution of the present work called Hierarchical MDRM algorithm (HMDRM). All these methods have been applied on dataset 2a of the BCI competition IV to facilitate their comparison. The highest accuracies were reached by the BCSP and HMDRM methods, confirming the effectiveness of hierarchical algorithms [7].

7.2.2.4. Discrete Motor Imageries for a Faster Detection

We are investigating differences between continuous MIs and discrete MIs corresponding to a 2s MI. Results show that both discrete and continuous MIs modulate ERD and ERS components. Both ERSs are different but ERDs are close in term of power of (de)synchronization. These results show that discrete motor imageries may be preferable for BCI systems design in order to faster detect MIs and reduce user fatigue. [8]

7.2.3. Pain under General Anaesthesia

Participants : Mariia Fedotenkova, Axel Hutt, Tamara Tošić

In collaboration with Peter beim Graben and James W. Sleigh.

7.2.3.1. Detection of EEG-signal Features for Pain under General Anaesthesia

Mariia Fedotenkova defended her thesis about extraction of multivariate components in brain signals obtained during general anesthesia. We studied analgesia effect of general anesthesia, more specifically, on patients reaction to nociceptive stimuli. We also study differences in the reaction between different anesthetic drugs. The study was conducted on a dataset consisting of 230 EEG signals: pre- and post-incision recordings obtained from 115 patients, who received desflurane and propofol. Combining features obtained with power spectral analysis and recurrence symbolic analysis [22], [6], [23], classification was carried out on a two-class problem, distinguishing between pre-/post-incision EEG signals, as well as between two different anesthetic drugs, desflurane and propofol [1].

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. CertiViBE

Laurent Bougrain is a member of the steering committee of OpenViBE and CertiViBE.

CertiViBE is a medically certifiable core for OpenViBE, the software for Brain Computer Interfaces and Neuroscience research. It is an Inria innovation lab to boost technology transfers from the Inria project-team Hybrid to Mensia Technologies SA (http://www.mensiatech.com/).

Founded in 2012, Mensia Technologies is a medical-device spin-off of Inria owning an exclusive worldwide license of the OpenViBE software for commercial applications. So far, OpenViBE has raised a lot of interest in the research community, especially on medical applications. However, OpenViBE being a research software, it does not yet match the requirements of medical devices in terms of stability, performance, documentation, as well as engineering processes in general, slowing down the transfer of OpenViBE-based medical research to industry. Within the CertiViBE project, Inria and Mensia Technologies are putting their task forces and respective expertise together to deliver a certifiable core for the OpenViBE software. While the OpenViBE software will continue to be published as an Open Source software, the project will dramatically facilitate the transfer of the research made with OpenViBE as it will be built on ready-to-certify foundations, following the processes and normative regulation of medical devices development including risk analysis, quality assurance and medical device software development and maintenance.

9. Partnerships and Cooperations

9.1. Regional Initiatives

In the *Contrat de Projet État Région (CPER) IT2MP* 2015-2020 on *Technological innovations, modeling and Personalized Medicine*, we are contributing on platform SCIARAT (*cognitive stimulation, Ambient Intelligence, Robotic assistance" and Telemedicine*). Contact in Neurosys is Laurent Bougrain.

9.2. National Initiatives

PEPS JCJC INS2I 2016 Modeling and simulation of the oscillatory activity of the memory system during sleep and under general anesthesia (L. Buhry, L. Bougrain).

In order to better understand the mechanisms of amnesia under anesthesia, we propose, on the one hand, to carry out a comparative study, to model and simulate the hippocampal oscillatory activity under general anesthesia and during sleep (tasks 1 and 2). Deep SEEG recordings in epileptic patients during seizures will serve as a reference for modeling and simulation. On the other hand, on the basis of data recorded during sleep, we wish (tasks 3 and 4) to analyze and model the interactions between two structures involved in memory, the hippocampus and the prefrontal cortex, and (tasks 5) propose an automated method to reveal markers of the hippocampal activity characteristics of the sleep stages making use of sole surface recordings. *As it is widely acknowledged that the consolidation of memory occurs mostly during the deep sleep stages, this should make it possible to distinguish the parts of the signal corresponding to periods of consolidation and to propose, through mathematical modeling and simulation, mechanisms explaining the effects of amnesia, or even the absence of memory formation under general anesthesia.

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

The *ITN*-project *Neural Engineering Transformative Technologies (NETT)*[0] (2012-2016) is a Europe-wide consortium of 18 universities, research institutes and private companies which together hosts 17 PhD students and 3 postdoctoral researchers over the past 4 years. Neural Engineering brings together engineering, physics, neuroscience and mathematics to design and develop brain-computer interface systems, cognitive computers and neural prosthetics. Contact is L. Bougrain.

[0] http://www.neural-engineering.eu/

9.4. International Initiatives

9.4.1. Inria International Partners

9.4.1.1. Informal International Partners

+ We have an ongoing collaboration with Prof. Motoharu Yoshida at the Ruhr University Bochum, Germany, aiming to study the role of persistent firing neurons in memory and more specifically in neural network synchronization. M. Yoshida provides us with biological data that we combine with simulations to test hypotheses on memory formation (L. Buhry).
+ We also collaborate with Prof. LieJune Shiau (University of Houston, Texas, USA) on more theoretical approaches concerning the role of intrinsic neuronal dynamics in network synchronization and brain oscillations (L. Buhry).

9.5. International Research Visitors

9.5.1. Visits of International Scientists

Prof. LieJune Shiau, University of Houston, June 2016. (collab. with L. Buhry)

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organization

10.1.1.1. Member of the Organizing Committees

- Member of the organization committee of the second OpenViBE workshop as a satellite event of the Brain-Computer Interfaces meeting, May 30th 2016, Asilomar, CA/USA (L. Bougrain) http://openvibe.inria.fr/the-2nd-international-openvibe-workshop-2016-contents/
- Member of the organization committee of the iPAC séminar (Image, Perception, Action et Cognition) (L. Buhry)

10.1.2. Scientific Events Selection

10.1.2.1. Member of the Conference Program Committees

- French conference on machine learning CAP 2016 (L. Bougrain)
- IEEE International Conference on Systems, Man, and Cybernetics (SMC) special sessions on Brain-Machine Interfaces, Budapest, 2016 (L. Bougrain)

10.1.2.2. Reviewer

- Brain-Computer Interfaces meeting 2016 (L. Bougrain)
- IEEE International Conference on Systems, Man, and Cybernetics (SMC) special sessions on Brain-Machine Interfaces, Budapest, 2016 (L. Bougrain)
- French conference on machine learning CAP 2016 (L. Bougrain)
- IEEE International Conference on Acoustic, Speech and Signal Processing - ICASSP, 2016 (T. Tošić)
- IEEE International Conference on Image Processing - ICIP, 2016. (T. Tošić)
- International Conference on Artificial Neural Networks (M. Fedotenkova)

10.1.3. Journal

10.1.3.1. Reviewer - Reviewing Activities

- L. Buhry is a reviewer for Journal of Computational Neuroscience, Frontiers in Computational Neuroscience, Journal of Neural Engineering, IEEE TNN (Transactions on Neural Networks), Neurocomputing, CCSP (Circuits, Sys. & Signal Proc.), IEEE international NEWCAS, Hippocampus
- T. Tošić is a reviewer for IEEE Transactions on Signal Processing (TSP), ACM Transactions on Sensor Networks (TOSN), Signal Processing : Image Communication

10.1.4. Invited Talks

- Active brain-computer interfaces and motor handicap compensation, IFRATH (Institut Fédératif de Recherche sur les Aides Techniques pour personnes Handicapées) and ITMO “Neurosciences, Sciences Cognitives, Neurologie, Psychiatrie”, feb. 4th 2017, INJS Paris (L. Bougrain)
- An introduction to OpenViBE, OpenViBE workshop, satellite event of the Brain-Computer Interfaces meeting, May 30th 2016, Asilomar, CA/USA (L. Bougrain) http://openvibe.inria.fr/the-2nd-international-openvibe-workshop-2016-contents/

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Engineering school: L. Bougrain, *Interfaces cerveau-ordinateur*, 4.5h, 3rd year, Supelec, France

Engineering school: T. Tošić, *Atelier Artem (Art-Technologie-Management) : ABCDWeb*, 30h, 2nd year, ICN, Ecole d’art et design, École des Mines Nancy, France

Engineering school: T. Tošić, *Parcours de recherche et Initiation à la recherche*, 11h, 2nd and 3rd year, Telecom Nancy and École des Mines Nancy, France

Engineering school: T. Tošić, *Apprentissage automatique - Modélisation avancée des connaissainces*, 58h, 3rd year, École des Mines Nancy, France

Engineering school: T. Tošić, *Tronc Commun d’Informatique - Python*, 140h, 1st year, École des Mines Nancy, France

Engineering school: T. Tošić, *Techniques et Solutions Informatiques*, 47h, 2nd year, École des Mines Nancy, France

Engineering school: T. Tošić, *Pépites Algorithmiques*, 18h, 1st year, École des Mines, France

Engineering school: T. Tošić, *Passerelle au Numérique*, 28h, 1st year, École des Mines, France

Engineering school: T. Tošić, *Model Driven Architecture and UML*, 21h, 2nd year, École des Mines, France

Engineering School: F. Giovannini, *Intelligence artificielle* (3rd year), 34h, Telecom Nancy, France

Licence: L. Buhry, *Applications en Sciences Cognitives*, 3h , niveau L1 MIASHS, University of Lorraine, France

Licence: L. Buhry, *Programmation Python*, 37h, level L1 MIASHS, University of Lorraine, France

Licence: L. Buhry *Probabilités-Statistiques*, 30h, level L1 MIASHS, University of Lorraine, France

Licence : L. Buhry, *IA et Résolution de problèmes*, 25h, level L3 MIASHS, University of Lorraine, France

Licence : L. Bougrain, *développement sur mobile*, 35h, Licence of computer science (3st year), University of Lorraine, France

Licence : L. Bougrain, *Intelligence artificielle*, 35h, Licence of computer science (3st year), University of Lorraine, France

Licence : L. Bougrain, *Optimisation*, 37.5h, Licence of computer science (3st year), University of Lorraine, France

Master : L. Buhry, *Algorithmique pour l’intelligence artificielle*, 31h, niveau Master 1 SCA (Sciences Cognitives et Applications), University of Lorraine, France

Master : L. Buhry, *IA fondamentale et fouille de données*, 18h, niveau Master 1 SCA (Sciences Cognitives et Applications), University of Lorraine, France

Master: L. Buhry, *Formalismes de Représentation et Raisonnement*, 25h, niveau Master 1 SCA (Sciences Cognitives et Applications), University of Lorraine, France

Master: L. Buhry, *Memory and Machine Learning*, 38h, niveau Master 1 SCA (Sciences Cognitives et Applications), University of Lorraine, France

Master : L. Buhry, *Neurosciences Computationnelles*, 25h, niveau Master 2 SCMN, University of Lorraine, France

Master : L. Bougrain, *Apprentissage automatique*, 18h, Master of computer science, 2st year, University of Lorraine, France

Master : L. Bougrain, *Facteurs humains*, 30h, Master of computer science 1st year, University of Lorraine, France

10.2.2. Supervision

PhD : Meysam Hashemi, Analytical and numerical studies of thalamo-cortical neural population models during general anesthesia, Univ. Lorraine, Jan. 14, 2016, A. Hutt [2]

PhD : Mariia Fedotenkova, Extraction of multivariate components in brain signals obtained during general anesthesia, Univ. Lorraine, Dec. 2, 2016, A. Hutt [1]

PhD in progress : Cecilia Lindig-Leon, Multilabel classification of EEG-based combined motor imageries implemented for the 3D control of a robotic arm, November 2013, A. Hutt and L. Bougrain

PhD in progress : Francesco Giovannini, Mathematical modelling of the memory system under general anesthesia, Oct. 2014, L. Buhry and A. Hutt

PhD in progress : Sébastien Rimbert Study of the dynamics of brain motor components during anesthesia, January 2016, A. Hutt and L. Bougrain

PhD in progress : Amélie Aussel, Extraction of electrophysiological markers and mathematical modeling of epileptic hippocampus, Oct. 2016, L. Buhry, Patrick Hénaff and R. Ranta

10.2.3. Juries

Laure Buhry was member of the PhD committee of Meysam Hashemi, University of Lorraine.

Laure Buhry was member of the PhD committee of Guillaume Viejo, Université Pierre et Marie Curie, Paris

10.3. Popularization

Interview and demo "Science on live" for the Science Festival 2016 at Cité des sciences et de l'industrie, Forum Explora about "Brain-Computer Interfaces for stroke rehabilitation" Oct. 8, 2016 (L. Bougrain, S. Rimbert). https://www.youtube.com/watch?v=cRCtGuvRW5A

Interview Huffington Post, Oct. 26, 2016 (L. Buhry)
(http://www.huffingtonpost.fr/2016/10/26/la-fille-du-train-creativite-imagination/)

Interview for Inria to introduce Neurosys' research on Brain-Computer Interfaces, Oct. 2016 (L. Bougrain) https://www.youtube.com/watch?v=DBajwAI9VEw at 5:38:10

Interview for the Regional TV news (JT 19/20 France 3 Lorraine): Brain-Computer Interfaces, Sept. 29, 2016 (L. Bougrain, S. Rimbert)

Talk during the National Brain Awareness Week: Brain, consciousness and waves, Mar. 18, 2016, Bibliothèque Multimédia Intercommunale, Epinal (L. Buhry, L. Koessler)

Interview for Radio CaraibNancy: Neuroscience in Lorraine, Mar. 16, 2016 (L. Bougrain, S. Caharel and L. Koessler)

Exhibit at Loria's open day for master students and engineers: controlling a robotic arm using EEG, Apr. 9, 2015 (L. Bougrain, J. Nex)

L. Bougrain & B. le Golvan, Neuroprosthetics, Evolution Psychiatrique, Elsevier [5] published on line on Mar. 8, 2016.

11. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] M. FEDOTENKOVA.*Extraction of multivariate components in brain signals obtained during general anesthesia*, Université de Lorraine, December 2016, https://hal.archives-ouvertes.fr/tel-01415998.

[2] M. HASHEMI.*Analytical and numerical studies of thalamo-cortical neural populationmodels during general anesthesia*, Université de Lorraine, January 2016, https://hal.inria.fr/tel-01265962.

Articles in International Peer-Reviewed Journal

[3] F. GIOVANNINI, B. KNAUER, M. YOSHIDA, L. BUHRY. *The CAN-In network: a biologically-inspired model for self-sustained theta oscillations and memory maintenance in the hippocampus* , in "Hippocampus", January 2017 [*DOI :* 10.1002/HIPO.22704], https://hal.archives-ouvertes.fr/hal-01426362.

[4] T. TOŠIĆ, K. K. SELLERS, F. FRÖHLICH, M. FEDOTENKOVA, P. BEIM GRABEN, A. HUTT.*Statistical Frequency-Dependent Analysis of Trial-to-Trial Variability in Single Time Series by Recurrence Plots*, in "Frontiers in Systems Neuroscience", January 2016, vol. 9, n^{o} 184 [*DOI :* 10.3389/FNSYS.2015.00184], https://hal.inria.fr/hal-01159664.

Articles in National Peer-Reviewed Journal

[5] L. BOUGRAIN, B. LE GOLVAN.*Les neuroprothèses*, in "L'Évolution Psychiatrique", March 2016, https://hal.inria.fr/hal-01287646.

Conferences without Proceedings

[6] M. FEDOTENKOVA, P. BEIM GRABEN, J. SLEIGH, A. HUTT.*Time-Frequency Representations as Phase Space Reconstruction in Recurrence Symbolic Analysis*, in "International work-conference on Time Series (ITISE)", Granada, Spain, June 2016, https://hal.archives-ouvertes.fr/hal-01343629.

[7] C. LINDIG-LEÓN, N. GAYRAUD, L. BOUGRAIN, M. CLERC.*Comparison of Hierarchical and Non-Hierarchical Classification for Motor Imagery Based BCI Systems*, in "The Sixth International Brain-Computer Interfaces Meeting", Pacific Groove, United States, May 2016, https://hal.inria.fr/hal-01287636.

[8] S. RIMBERT, L. BOUGRAIN.*Comparison Between Discrete and Continuous Motor Imageries: toward a Faster Detection*, in "International Brain Computer Interface Meeting 2016", California, United States, May 2016, https://hal.inria.fr/hal-01389948.

Scientific Books (or Scientific Book chapters)

[9] L. BOUGRAIN.*Applications médicales: neuroprothèses et neuroadaptation*, in "Brain-Computer Interfaces", M. CLERC, L. BOUGRAIN (editors), Technologie et Applications, ISTE, July 2016, vol. 2, https://hal.inria.fr/hal-01429026.

[10] L. BOUGRAIN.*Medical Applications: Neuroprostheses and Neurorehabilitation*, in "Brain-Computer Interfaces", M. CLERC, L. BOUGRAIN, F. LOTTE (editors), Technology and Applications, Wiley-ISTE, July 2016, vol. 2, https://hal.inria.fr/hal-01429029.

[11] L. BOUGRAIN, G. SERRIÈRE.*Classification de signaux cérébraux avec OpenViBE*, in "Interfaces cerveau-ordinateur", M. CLERC (editor), Technologie et Applications, ISTE, July 2016, vol. 2, https://hal.inria.fr/hal-01429035.

[12] L. BOUGRAIN, G. SERRIÈRE.*Classification of Brain Signals with OpenViBE* , in "Brain-Computer Interfaces", M. CLERC, L. BOUGRAIN, F. LOTTE (editors), Technology and Applications, Wiley-ISTE, July 2016, vol. 2, https://hal.inria.fr/hal-01429033.

[13] M. CLERC, L. BOUGRAIN, F. LOTTE.*Conclusion and Perspectives*, in "Brain-Computer Interfaces 2", Wiley-ISTE, July 2016, https://hal.inria.fr/hal-01409032.

[14] M. CLERC, L. BOUGRAIN, F. LOTTE.*Conclusion et perspectives*, in "Les interfaces cerveau-ordinateur 2", ISTE, July 2016, https://hal.inria.fr/hal-01408972.

[15] M. CLERC, L. BOUGRAIN, F. LOTTE.*Introduction*, in "Brain-Computer Interfaces 1", M. CLERC, L. BOUGRAIN, F. LOTTE (editors), Wiley-ISTE, July 2016, https://hal.inria.fr/hal-01409001.

[16] M. CLERC, L. BOUGRAIN, F. LOTTE.*Introduction*, in "Les interfaces cerveau-ordinateur 1", M. CLERC, L. BOUGRAIN, F. LOTTE (editors), Fondements et méthodes, ISTE, July 2016, https://hal.inria.fr/hal-01402594.

Books or Proceedings Editing

[17] M. CLERC, L. BOUGRAIN, F. LOTTE (editors). *Brain-Computer Interfaces 1: Foundations and Methods*, Wiley-ISTE, July 2016, https://hal.inria.fr/hal-01408991.

[18] M. CLERC, L. BOUGRAIN, F. LOTTE (editors). *Brain-Computer Interfaces 2: Technology and Applications*, Wiley-ISTE, July 2016, https://hal.inria.fr/hal-01408998.

[19] M. CLERC, L. BOUGRAIN, F. LOTTE (editors). *Les interfaces Cerveau-Ordinateur 1 : Fondements et méthodes*, ISTE, July 2016, https://hal.inria.fr/hal-01402539.

[20] M. CLERC, L. BOUGRAIN, F. LOTTE (editors). *Les interfaces cerveau-ordinateur 2 : Technologie et applications*, ISTE, July 2016, https://hal.inria.fr/hal-01402544.

Scientific Popularization

[21] S. RIMBERT, S. FLECK, J. NEX, L. BOUGRAIN.*Nécessité d'un protocole d'apprentissage progressif pour la maîtrise d'une imagination motrice après un AVC*, in "28ième conférence francophone sur l'Interaction

Homme-Machine", Fribourg, Switzerland, Atelier sur les Nouvelles technologies pour les Ainées, défis et perspectives, October 2016, p. 10-12, https://hal.archives-ouvertes.fr/hal-01386665.

Other Publications

[22] M. FEDOTENKOVA, P. BEIM GRABEN, J. SLEIGH, A. HUTT.*Time-Frequency Representations as Phase Space Reconstruction in Symbolic Recurrence Structure Analysis*, December 2016, To appear as a book chapter in the Springer series “Contributions to Statistics”, https://hal.archives-ouvertes.fr/hal-01415997.

[23] M. FEDOTENKOVA, P. BEIM GRABEN, T. TOŠIĆ, J. SLEIGH, A. HUTT.*Recurrence complexity analysis of oscillatory signals with application to general anesthesia EEG signals*, May 2016, Submitted to Physics Letters A, https://hal.archives-ouvertes.fr/hal-01343631.

[24] F. GIOVANNINI, B. KNAUER, M. YOSHIDA, L. BUHRY.*Spiking regimes in model networks of hippocampal persistent firing neurons*, November 2016, Neuroscience 2016, Poster, https://hal.inria.fr/hal-01402515.

Project-Team ORPAILLEUR

Knowledge discovery, knowledge engineering

IN COLLABORATION WITH: Laboratoire lorrain de recherche en informatique et ses applications (LORIA)

IN PARTNERSHIP WITH:
CNRS

Université de Lorraine

RESEARCH CENTER
Nancy - Grand Est

THEME
Data and Knowledge Representation and Processing

Table of contents

Project-Team ORPAILLEUR

Creation of the Project-Team: 2008 January 01

Keywords:

Computer Science and Digital Science:

3. - Data and knowledge
3.1.1. - Modeling, representation
3.1.7. - Open data
3.2. - Knowledge
3.2.1. - Knowledge bases
3.2.2. - Knowledge extraction, cleaning
3.2.3. - Inference
3.2.4. - Semantic Web
3.2.5. - Ontologies
3.3.2. - Data mining
3.3.3. - Big data analysis
3.4.1. - Supervised learning
3.4.2. - Unsupervised learning
3.4.5. - Bayesian methods
3.4.8. - Deep learning
3.5.2. - Recommendation systems
4. - Security and privacy
4.1. - Threat analysis
7.2. - Discrete mathematics, combinatorics
7.9. - Graph theory
8. - Artificial intelligence
8.1. - Knowledge
8.2. - Machine learning
8.6. - Decision support

Other Research Topics and Application Domains:

1.1.2. - Molecular biology
1.2. - Ecology
1.2.1. - Biodiversity
2. - Health
2.3. - Epidemiology
2.4.1. - Pharmaco kinetics and dynamics
2.4.2. - Drug resistance
3.1. - Sustainable development
3.5. - Agronomy
3.6. - Ecology
3.6.1. - Biodiversity
6.3.4. - Social Networks

6.4. - Internet of things
8.5.2. - Crowd sourcing
9. - Society and Knowledge
9.4.5. - Data science

1. Members

Research Scientists

Amedeo Napoli [Team leader, CNRS, Senior Researcher, HDR]
Esther Galbrun [Researcher, Inria]
Chedy Raïssi [Researcher, Inria]
Jean-Sébastien Sereni [Researcher, CNRS]

Faculty Members

Miguel Couceiro [Univ. Lorraine, Professor, HDR]
Adrien Coulet [Univ. Lorraine, Associate Professor]
Nicolas Jay [Univ. Lorraine, Professor, HDR]
Florence Le Ber [ENGEES Strasbourg, Professor (Team Associate), HDR]
Jean Lieber [Univ. Lorraine, Associate Professor, HDR]
Jean-François Mari [Univ. Lorraine, Professor, HDR]
Emmanuel Nauer [Univ. Lorraine, Associate Professor]
Sébastien Da Silva [Univ. Lorraine, Associate Professor]
Malika Smaïl-Tabbone [Univ. Lorraine, Associate Professor, HDR]
Yannick Toussaint [Univ. Lorraine, Professor (since Sep 2016, formerly Inria Researcher), HDR]

Technical Staff

Jérémie Nevin [Univ. Lorraine]
Thi Nhu Nguyen Le [Inria]
Mickaël Zehren [Inria, until May 2016]

PhD Students

Quentin Brabant [Univ. Lorraine]
Kévin Dalleau [Univ. Lorraine, since Dec 2016]
Rémi de Joannis de Verclos [Univ. Grenoble-Alpes]
Nyoman Juniarta [Univ. Lorraine, since Dec 2016]
Pierre Monnin [Univ. Lorraine, since Sep 2016]
François Pirot [Univ. Lorraine/Univ. Nijmegen, since Oct 2016]
Justine Reynaud [Inria]
Mohsen Sayed [Univ. Lorraine]
My Thao Tang [Univ. Lorraine, until June 2016]

Post-Doctoral Fellows

Emmanuelle Gaillard [Univ. Lorraine, ATER]
Dhouha Grissa [INRA]
Joël Legrand [Univ. Lorraine, since Nov 2016]

Visiting Scientist

Lucien Haddad [Visiting Scientist, until Mar 2016]

Administrative Assistants

Antoinette Courrier [CNRS]
Emmanuelle Deschamps [Inria]
Sylvie Musilli [Univ. Lorraine]

Others

Aurore Alcolei [ENS Lyon, Student, until March 2016]
Marie Blemus [Inria, Student, from Jun 2016 until Aug 2016]
Yelen Per [CNRS, Student (Alternance)]

2. Overall Objectives

2.1. Introduction

Knowledge discovery in databases (KDD) consists in processing large volumes of data in order to discover knowledge units that are significant and reusable. Assimilating knowledge units to gold nuggets, and databases to lands or rivers to be explored, the KDD process can be likened to the process of searching for gold. This explains the name of the research team: in French "orpailleur" denotes a person who is searching for gold in rivers or mountains. The KDD process is based on three main operations: data preparation, data mining and interpretation of the extracted units as knowledge units. Moreover, the KDD process is iterative, interactive, and generally controlled by an expert of the data domain, called the analyst. The analyst selects and interprets a subset of the extracted units for obtaining knowledge units having a certain plausibility.

As a person searching for gold may have a certain experience about the task and the location, the analyst may use general and domain knowledge for improving the whole KDD process. Accordingly, the KDD process may be related to knowledge bases (or domain ontologies) related to the domain of data for implementing *knowledge discovery guided by domain knowledge* or KDDK. In the KDDK process, the extracted units have "a life" after the interpretation step: they are represented as knowledge units using a knowledge representation formalism and integrated within an ontology to be reused for problem-solving needs. In this way, knowledge discovery extends and updates existing knowledge bases, reifying the complementarity of knowledge discovery and knowledge representation.

3. Research Program

3.1. Knowledge Discovery guided by Domain Knowledge

Keywords: knowledge discovery in databases, knowledge discovery in databases guided by domain knowledge, data mining formal concept analysis, classification, pattern mining second-order Hidden Markov Models

Knowledge discovery in databases (KDD) is aimed at discovering patterns in large databases. These patterns can then be interpreted as knowledge units to be reused in knowledge systems. From an operational point of view, the KDD process is based on three main steps: (i) selection and preparation of the data, (ii) data mining, (iii) interpretation of the discovered patterns. The KDD process –as implemented in the Orpailleur team– is based on data mining methods which are either symbolic or numerical. Symbolic methods are based on pattern mining (e.g. mining frequent itemsets, association rules, sequences...), Formal Concept Analysis (FCA [80]) and extensions of FCA such as Pattern Structures [83] and Relational Concept Analysis (RCA [90]). Numerical methods are based on probabilistic approaches such as second-order Hidden Markov Models (HMM [85]), which are well adapted to the mining of temporal and spatial data.

Domain knowledge, when available, can improve and guide the KDD process, materializing the idea of *Knowledge Discovery guided by Domain Knowledge* or KDDK. In KDDK, domain knowledge plays a role at each step of KDD: the discovered patterns can be interpreted as knowledge units and reused for problem-solving activities in knowledge systems, implementing the operational sequence "mining, interpreting (modeling), representing, and reasoning". In this way, knowledge discovery appears as a core task in knowledge engineering, with an impact in various semantic activities, e.g. information retrieval, recommendation and ontology engineering. Usual application domains for the team include agronomy, astronomy, biology, chemistry, and medicine.

One main operation in the research work of Orpailleur on KDDK is *classification*, which is a polymorphic process involved in modeling, mining, representing, and reasoning tasks. Classification problems can be formalized by means of a class of objects (or individuals), a class of attributes (or properties), and a binary correspondence between the two classes, indicating for each individual-property pair whether the property applies to the individual or not. The properties may be features that are present or absent, or the values of a property that have been transformed into binary variables. Formal Concept Analysis (FCA) relies on the analysis of such binary tables and may be considered as a symbolic data mining technique to be used for extracting a set of formal concepts then organized within a concept lattice [80] (concept lattices are also known as “Galois lattices” [68]).

In parallel, the search for frequent itemsets and the extraction of association rules are well-known symbolic data mining methods, related to FCA (actually searching for frequent itemsets can be understood as traversing a concept lattice). Both processes usually produce a large number of items and rules, leading to the associated problems of “mining the sets of extracted items and rules”. Some subsets of itemsets, e.g. frequent closed itemsets (FCIs), allow finding interesting subsets of association rules, e.g. informative association rules. This explains why several algorithms are needed for mining data depending on specific applications [92].

3.2. Text Mining

Keywords: text mining, knowledge discovery form collection of texts, annotation, ontology engineering from texts

The objective of a text mining process is to extract useful knowledge units from large collections of texts [78]. The text mining process shows specific characteristics due to the fact that texts are complex objects written in natural language. The information in a text is expressed in an informal way, following linguistic rules, making text mining a particular task. To avoid information dispersion, a text mining process has to take into account –as much as possible– paraphrases, ambiguities, specialized vocabulary and terminology. This is why the preparation of texts for text mining is usually dependent on linguistic resources and methods.

From a KDDK perspective, text mining is aimed at extracting “interesting units” (nouns and relations) from texts with the help of domain knowledge encoded within an ontology (also useful for text annotation). Text mining is especially useful in the context of semantic web for ontology engineering. In the Orpailleur team, the focus is put on the mining of real-world texts in application domains such as biology and medicine, using mainly symbolic data mining methods, and especially Formal Concept Analysis. Accordingly, the text mining process may be involved in a loop used to enrich and to extend linguistic resources. In turn, linguistic and ontological resources can be exploited to guide a “knowledge-based text mining process”.

3.3. Knowledge Systems and Web of Data

Keywords: knowledge engineering, web of data, semantic web, ontology, description logics, classification-based reasoning, case-based reasoning, information retrieval

The web of data constitutes a good platform for experimenting ideas on knowledge engineering and knowledge discovery, in relation with the principles of semantic web. A software agent may be able to read, understand, and manipulate information on the web, if and only if the knowledge necessary for achieving those tasks is available: this is why domain knowledge and ontologies are of main importance. The knowledge representation language recommended by W3C to design ontologies and knowledge bases is OWL, which is based on description logics (DLs [65]). In OWL, knowledge units are represented by classes (DL concepts) having properties (DL roles) and instances. Concepts are organized within a partial order based on a subsumption relation, and the inference services are based on classification-based reasoning and case-based reasoning (CBR).

Actually, there are many interconnections between concept lattices in FCA and ontologies, e.g. the partial order underlying an ontology can be supported by a concept lattice. Moreover, a pair of implications within a concept lattice can be adapted for designing concept definitions in ontologies. Accordingly, we are interested here in two main challenges: how the web of data, as a set of potential knowledge sources (e.g. DBpedia, Wikipedia, Yago, Freebase...) can be mined for helping the design of definitions and knowledge bases and how knowledge discovery techniques can be applied for providing a better usage of the web of data (e.g. LOD classification).

Accordingly, a part of the research work in Knowledge Engineering is oriented towards knowledge discovery in the web of data, as, with the increased interest in machine processable data, more and more data is now published in RDF (Resource Description Framework) format. Particularly, we are interested in the completeness of the data and their potential to provide concept definitions in terms of necessary and sufficient conditions [66]. We have proposed a novel technique based on FCA which allows data exploration as well as the discovery of definition (bidirectional implication rules).

4. Application Domains

4.1. Life Sciences: Biology, Chemistry and Medicine

Participants: Adrien Coulet, Nicolas Jay, Joël Legrand, Jean Lieber, Pierre Monnin, Amedeo Napoli, Chedy Raïssi, Mohsen Sayed, Malika Smaïl-Tabbone, Yannick Toussaint, Mickaël Zehren.

Keywords: knowledge discovery in life sciences, bioinformatics, biology, chemistry, medicine, pharmacogenomics

One major application domain which is currently investigated by the Orpailleur team is related to life sciences, with particular emphasis on biology, medicine, and chemistry. The understanding of biological systems provides complex problems for computer scientists, and the developed solutions bring new research ideas or possibilities for biologists and for computer scientists as well. Indeed, the interactions between researchers in biology and researchers in computer science improve not only knowledge about systems in biology, chemistry, and medicine, but knowledge about computer science as well.

Knowledge discovery is gaining more and more interest and importance in life sciences for mining either homogeneous databases such as protein sequences and structures, or heterogeneous databases for discovering interactions between genes and environment, or between genetic and phenotypic data, especially for public health and pharmacogenomics domains. The latter case appears to be one main challenge in knowledge discovery in biology and involves knowledge discovery from complex data depending on domain knowledge.

On the same line as biological data, chemical data are presenting important challenges w.r.t. knowledge discovery, for example for mining collections of molecular structures and collections of chemical reactions in organic chemistry. The mining of such collections is an important task for various reasons among which the challenge of graph mining and the industrial needs (especially in drug design, pharmacology and toxicology). Molecules and chemical reactions are complex data that can be modeled as undirected labeled graphs. Graph mining methods may play an important role in this framework and Formal Concept Analysis can also be used in an efficient and well-founded way [86]. Graph mining in the framework of FCA is a very important task on which we are working, whose results can be transferred to text mining as well.

We are working on knowledge management in medicine and analysis of patient trajectories. The Kasimir research project is about decision support and knowledge management for the treatment of cancer. This is a multidisciplinary research project in which researchers in computer science (Orpailleur) and experts in oncology are participating. For a given cancer localization, a treatment is based on a protocol, which is applied in 70% of the cases and provides a treatment. The 30% remaining cases are “out of the protocol”, e.g. contraindication, treatment impossibility, etc. and the protocol should be adapted, based on discussions among specialists. This adaptation process is modeled in Kasimir thanks to CBR, where semantic web technologies are used and adapted for several years.

The analysis of patient trajectories, i.e. the "path" of a patient during illness (chronic illnesses and cancer), can be considered as an analysis of sequences. It is important to understand such sequential data and sequence mining methods should be adapted for addressing the complex nature of medical events. We are interested in the analysis of trajectories at different levels of granularity and w.r.t. external domain ontologies. In addition, it is also important to be able to compare and classify trajectories according to their content. Then we are also interested in the definition of similarity measures able to take into account the complex nature of trajectories and that can be efficiently implemented for allowing quick and reliable classifications.

PractiKPharma (Practice-based evidences for actioning Knowledge in Pharmacogenomics) is a starting research project about the validation of state-of-the-art knowledge in pharmacogenomics by mining "Electronic Health Records" (EHRs) [55]. Pharmacogenomics is a field studying how genomic variations impact drug responses. Most of the state of the art in the field is only available in biomedical literature, with various levels of validation. Accordingly we propose firstly, to extract pharmacogenomic knowledge units from the literature and secondly, to confirm or moderate these units by mining EHRs. Comparing knowledge units extracted form the literature with facts extracted from EHRs is not a trivial task for several reasons, among which (i) the literature is in English, whereas EHRs are in French, (ii) EHRs represent observations at the patient level whereas the literature is generalizing sets of patients...

4.2. Cooking

Participants: Emmanuelle Gaillard, Jean Lieber, Emmanuel Nauer.

Keywords: cooking, knowledge engineering, case-based reasoning, semantic web

123 The origin of the Taaable project is the Computer Cooking Contest (CCC). A contestant to CCC is a system that answers queries about recipes, using a recipe base; if no recipe exactly matches the query, then the system adapts another recipe. Taaable is a case-based reasoning system based on various technologies from semantic web, knowledge discovery, knowledge representation and reasoning. From a research viewpoint the system enables to test scientific results and to study the complementarity of various research trends in an application domain which is simple to understand and which raises complex issues at the same time.

4.3. Agronomy

Participants: Sébastien Da Silva, Florence Le Ber, Jean-François Mari.

Keywords: simulation in agronomy, graph model in agronomy

Research in agronomy was conducted in the framework of an Inria-INRA collaboration, taking place in the INRA research network PAYOTE about landscape modeling. In this framework, Sébastien da Silva prepared and defended a PhD thesis [74] in September 2014, supervised by Claire Lavigne (DR in ecology, INRA Avignon) and Florence Le Ber. The research work was related to the characterization and the simulation of hedgerow structures in agricultural landscapes, based on Hilbert-Peano curves and Markov models [48].

Moreover, an on-going research work about the representation of peasant knowledge is involved within a collaboration with IRD in Madagascar [81]. Sketches drawn by peasants were transformed into graphs and compared thanks to Formal Concept Analysis.

4.4. Digital Humanities

Participant: Jean Lieber.

Keywords: digital humanities, semantic web, SPARQL, approximate search, case-based reasoning

Recent contacts with the digital humanity community occurred with a group of researchers working in history and philosophy of science and technologies (located in Brest, Montpellier and Nancy). They want to benefit from semantic Web technologies in order to provide better accesses to their text corpora. A paper based on this starting collaboration was published [69], about exact and approximate search in RDFS-annotated text corpora based on the SPARQL technology and on case-based reasoning principles.

5. Highlights of the Year

5.1. Highlights of the Year

- The conference paper got the best paper award at the International Conference on Concept Lattices and Applications 2016 in Moscow, July 2016 (https://cla2016.hse.ru/awards). This reward was given to the paper and also to the whole work on the formalization of functional dependencies done by the four authors during the last years.
- In July 2016, Chedy Raïssi visited NASA Ames and SETI Institute as part of the Frontier Development Lab. He worked there for six weeks on the planetary defense community and focused on Delay-Doppler radar imaging. This stay was organized in the framework of the NASA "Asteroid Grand Challenge" program, where participation is based on a strong selection process.

BEST PAPERS AWARDS :

[33] **Thirteenth International Conference on Concept Lattices and Their Applications (CLA 2016)**. V. CODOCEDO, J. BAIXERIES, M. KAYTOUE, A. NAPOLI.

6. New Software and Platforms

6.1. Symbolic KDD Systems

6.1.1. LatViz

- Contact: Thi Nhu Nguyen Le
- URL: http://latviz.loria.fr/latviz/
- KEYWORDS: Formal Concept Analysis, Pattern Mining, Concept Lattice, Implications, Visualization

FUNCTIONAL DESCRIPTION.

LatViz is a new tool which allows the construction, the display and the exploration of concept lattices. LatViz proposes some remarkable improvements over existing tools and introduces various new functionalities focusing on interaction with experts, such as visualization of pattern structures (for dealing with complex non-binary data), AOC-posets (the core elements of the lattice), concept annotations, filtering based on various criteria and a visualization of implications [28], [27]. This way the user can effectively perform interactive exploratory knowledge discovery as often needed in knowledge engineering.

The Latviz platform can be associated with the Coron platform and extends its visualization capabilities (see http://coron.loria.fr). Recall that the Coron platform includes a complete collection of data mining algorithms for extracting itemsets and association rules.

6.1.2. OrphaMine – Data mining platform for orphan diseases

- Partners: INSERM – MoDYCo CNRS – Greyc Université de Caen Basse Normandie
- Contact: Chedy Raïssi
- URL: http://orphamine.inria.fr/
- KEYWORDS: Bioinformatics, data mining, biology, health, data visualization, drug development.

FUNCTIONAL DESCRIPTION.

The OrphaMine platform, developed as part of the ANR Hybrid project, enables visualization, data integration and in-depth analytics. The data at the heart of the platform is about orphan diseases and is extracted from the OrphaData ontology (http://www.orpha.net).

We aim at building a true collaborative portal that will serve the different actors of the Hybrid project: (i) A general visualization of OrphaData data for physicians working, maintaining and developing this knowledge database about orphan diseases. (ii) The integration of analytics (data mining) algorithms developed by the different academic actors. (iii) The use of these algorithms to improve our general knowledge of rare diseases.

6.1.3. POQEMON Analytics: Platform for Quality Evaluation of Mobile Networks

- Partners: Altran, DataPublica, GenyMobile, HEC, Inria Nancy-Grand Est, IP-Label, Next Interactive Media, Orange, Université Paris-Est Créteil
- Contact: Chedy Raïssi
- URL: https://members.loria.fr/poqemon/
- KEYWORDS: Data mining, data visualization.

FUNCTIONAL DESCRIPTION.

POQEMON is a quality evaluation platform for mobile phone networks developed in the Orpailleur team in the frameowrok of an FUI project (see 8.2.2). The quality measures which are studied include the coverage, availability and network performances. Multiple methods are implemented in this platform, either in visualization or in data anonymization to make on-line analytics as simple as possible.

6.1.4. Siren - Interactive and visual redescription mining

- Contact: Esther Galbrun
- URL: http://siren.gforge.inria.fr/main/
- KEYWORDS: Redescription mining, Interactivity, Visualization.

FUNCTIONAL DESCRIPTION.

Siren is a tool for interactive mining and visualization of redescriptions. Redescription mining aims to find distinct common characterizations of the same objects and, vice versa, to identify sets of objects that admit multiple shared descriptions. The goal is to provide domain experts with a tool allowing them to tackle their research questions using redescription mining. Merely being able to find redescriptions is not enough. The expert must also be able to understand the redescriptions found, adjust them to better match his domain knowledge and test alternative hypotheses with them, for instance. Thus, Siren allows mining redescriptions in an anytime fashion through efficient, distributed mining, to examine the results in various linked visualizations, to interact with the results either directly or via the visualizations, and to guide the mining algorithm toward specific redescriptions.

6.2. Stochastic systems for knowledge discovery and simulation

6.2.1. The CarottAge and ARPEnTAge Systems

- Contact: Jean-François Mari
- URL:http://carottage.loria.fr
- KEYWORDS: Stochastic process, Hidden Markov Models.

FUNCTIONAL DESCRIPTION.

The system CarottAge is based on Hidden Markov Models of second order and provides a non supervised temporal clustering algorithm for data mining [84]. CarottAge is currently used by INRA researchers interested in mining the changes in territory and landscape related to the loss of biodiversity (projects ANR BiodivAgrim and ACI Ecoger) and/or water contamination. CarottAge was also used for mining hydromorphological data and gave interesting results for that purpose.

ARPEnTAge, for "*Analyse de Régularités dans les Paysages : Environnement, Territoires, Agronomie*" is built on top of the CarottAge system to fully take into account the spatial dimension of input sequences. It can be used for analyzing spatio-temporal databases [85] and for space-time clustering of a landscape based on temporal land uses. Displaying tools and the generation of time-dominant shape files have also been defined. With agronomists, we are now focusing on the simulation of unknown spatial time sequences in order to explore various crop management scenarios.

CarottAge and ARPEnTAge are freely available under GPL license. A special effort is currently aimed at designing interactive visualization tools to provide the expert a user-friendly interface.

7. New Results

7.1. The Mining of Complex Data

Participants: Quentin Brabant, Miguel Couceiro, Adrien Coulet, Esther Galbrun, Nicolas Jay, Nyoman Juniarta, Florence Le Ber, Joël Legrand, Pierre Monnin, Amedeo Napoli, Justine Reynaud, Chedy Raïssi, Mohsen Sayed, My Thao Tang, Yannick Toussaint.

Keywords: formal concept analysis, relational concept analysis, pattern structures, pattern mining, association rule, redescription mining, graph mining, sequence mining, biclustering, aggregation

Pattern mining and Formal Concept Analysis are suitable symbolic methods for KDDK, that may be used for real-sized applications. Global improvements are carried out on the scope of applicability, the ease of use, the efficiency of the methods, and on the ability to fit evolving situations. Accordingly, the team is extending these symbolic data mining methods for working on complex data (e.g. textual documents, biological, chemical or medical data), involving objects with multi-valued attributes (e.g. domains or intervals), n-ary relations, sequences, trees and graphs.

7.1.1. FCA and Variations: RCA, Pattern Structures and Biclustering

Advances in data and knowledge engineering have emphasized the needs for pattern mining tools working on complex data. In particular, FCA, which usually applies to binary data-tables, can be adapted to work on more complex data. In this way, we have contributed to two main extensions of FCA, namely Pattern Structures and Relational Concept Analysis. Pattern Structures (PS [79]) allow building a concept lattice from complex data, e.g. numbers, sequences, trees and graphs. Relational Concept Analysis (RCA) is able to analyze objects described both by binary and relational attributes [90] and can play an important role in text classification and text mining.

Many developments were carried out in pattern mining and FCA for improving data mining algorithms and their applicability, and for solving some specific problems such as information retrieval, discovery of functional dependencies and biclustering. We designed new information retrieval methods based on FCA [72], text classification and heterogeneous pattern structures [71], pattern structures for structured attribute sets [67], and also a quasi-polynomial algorithm for mining top patterns w.r.t. measures satisfying special properties in a FCA framework [70]. We developed also a whole line of work on pattern structures for the discovery of functional dependencies [33], text classification and heterogeneous pattern structures [71], and fuzzy FCA as well [31]. Finally, we also proposed new visualization techniques and tools able to display important and useful information (e.g. stable concepts) from large concept lattices [28].

7.1.2. Text Mining

The thesis work of My Thao Tang [11] proposes a process where software and humans agents cooperate in knowledge discovery from different source textual types for extending a knowledge base. One challenge is that, on the one hand, knowledge discovery methods (software agents) can be run in accordance with background knowledge (or expert knowledge), at any step of the KDD process. On the other hand, human agents should be able to correct or to extend the current knowledge base. FCA is used for discovering a "class schema" (or "representation model") within textual resources which can be either a set of attribute implications or a concept lattice. However, such a schema does not necessarily fit the point of view of a domain expert for different reasons, e.g. noise, errors or exceptions in the data. Thus, a bridge filling the possible gap between the representation model based on a concept lattice and the representation model of a domain expert is studied in [44]. The background knowledge is encoded as a set of attribute dependencies or constraints which is "aligned" with the set of implications associated with the concept lattice. Such an alignment may lead to modifications in the original concept lattice. This method can be generalized for generating lattices satisfying some constraints based on attribute dependencies in using the so-called "extensional projections". It also allows experts to keep a trace of the changes occurring in the original lattice and the revised version, and to assess how concepts in practice are related to concepts discovered in the data.

In the framework of the Hybride ANR project (see 8.2.1.1), Mohsen Sayed proposes an original machine learning approach for identifying in literature disease phenotypes that are not yet represented within existing ontologies. The process is based on graph patterns extracted from sentences represented as dependency graphs. Phenotypes are usually expressed by complex noun phrases while traditional gazetteers recognize them only partially. The strength of graph patterns is to preserve the linguistic component bounds and to enable the identification of the complete phenotype formulation. A specific publication is currently in preparation.

7.1.3. Mining Sequences and Trajectories

Nowadays data sets are available in very complex and heterogeneous ways. Mining of such data collections is essential to support many real-world applications ranging from healthcare to marketing. This year, we completed a research work on the analysis of "complex sequential data" by means of interesting sequential patterns [13]. We approach the problem using FCA and pattern structures, where the subsumption relation ordering patterns is defined w.r.t. the partial order on sequences.

7.1.4. Redescription Mining

Among the mining methods developed in the team is redescription mining. Redescription mining aims to find distinct common characterizations of the same objects and, vice versa, to identify sets of objects that admit multiple shared descriptions [89]. It is motivated by the idea that in scientific investigations data oftentimes have different nature. For instance, they might originate from distinct sources or be cast over separate terminologies. In order to gain insight into the phenomenon of interest, a natural task is to identify the correspondences that exist between these different aspects.

A practical example in biology consists in finding geographical areas that admit two characterizations, one in terms of their climatic profile and one in terms of the occupying species. Discovering such redescriptions can contribute to better our understanding of the influence of climate over species distribution. Besides biology, applications of redescription mining can be envisaged in medicine or sociology, among other fields.

In recent work [40], we focused on the problem of pattern selection, developing a method for filtering a set of redescription to identify a non-redundant, interesting subset to present to the analyst. Also, we showcased the usability of redescription mining on an application in the political domain [50]. More specifically, we applied redescription mining to the exploratory analysis of the profiles and opinions of candidates to the parliamentary elections in Finland in 2011 and 2015.

We presented an introductory tutorial on redescription mining at ECML-PKDD in September 2016 to help foster the research on these techniques and widen their use (http://siren.mpi-inf.mpg.de/tutorial/main/).

7.1.5. E-sports analytics and subgroup discovery based on a single-player game

Discovering patterns that strongly distinguish one class label from another is a challenging data-mining task. The unsupervised discovery of such patterns would enable the construction of intelligible classifiers and to elicit interesting hypotheses from the data. Subgroup Discovery (SD) [87] is one framework that formally defines this pattern mining task. However, SD still faces two major issues: (i) how to define appropriate quality measures to characterize the uniqueness of a pattern; (ii) how to select an accurate heuristic search technique when exhaustive enumeration of the pattern space is unfeasible. The first issue has been tackled by the Exceptional Model Mining (EMM) framework [77]. This general framework aims to find patterns that cover tuples that locally induce a model that substantially differs from the model of the whole dataset. The second issue has been studied in SD and EMM mainly with the use of beam-search strategies and genetic algorithms for discovering a pattern set that is non-redundant, diverse and of high quality. In [58], we argue that the greedy nature of most of these approaches produce pattern sets that lack of diversity. Consequently, we proposed to formally define pattern mining as a single-player game, as in a puzzle, and to solve it with a Monte Carlo Tree Search (MCTS), a recent technique mainly used for artificial intelligence and planning problems. The exploitation/exploration trade-off and the power of random search of MCTS lead to an any-time mining approach, in which a solution is always available, and which tends towards an exhaustive search if given enough time and memory. Given a reasonable time and memory budget, MCTS quickly drives the search towards a diverse pattern set of high quality. MCTS does not need any knowledge of the pattern quality measure, and we show to what extent it is agnostic to the pattern language.

7.1.6. Data Privacy: Online link disclosure strategies for social networks

Online social networks are transforming our culture and world. While online social networks have become an important channel for social interactions, they also raise ethical and privacy issues. A well known fact is that social networks leak information, that may be sensitive, about users. However, performing accurate real world online privacy attacks in a reasonable time frame remains a challenging task. In [57], [26] (this work is done in cooperation with the Pesto Inria Team), we address the problem of rapidly disclosing many friendship links using only legitimate queries (i.e., queries and tools provided by the targeted social network). Our study sheds new light on the intrinsic relation between communities (usually represented as groups) and friendships between individuals. To develop an efficient attack we analyzed group distributions, densities and visibility parameters from a large sample of a social network. By effectively exploring the target group network, our proposed algorithm is able to perform friendship and mutual-friend attacks along a strategy that minimizes the number of queries. The results of attacks performed on a major social network profiles show that 5 different friendship links are disclosed in average for each single legitimate query in the best cases.

7.1.7. Aggregation

Aggregation theory is the study of processes dealing with the problem of merging or fusing several objects, e.g., numerical or qualitative data, preferences or other relational structures, into a single or several objects of similar type and that best represents them in some way. Such processes are modeled by so-called aggregation or consensus functions [82]. The need to aggregate objects in a meaningful way appeared naturally in classical topics such as mathematics, statistics, physics and computer science, but it became increasingly emergent in applied areas such as social and decision sciences, artificial intelligence and machine learning, biology and medicine.

We are working on a theoretical basis of a unified theory of consensus and to set up a general machinery for the choice and use of aggregation functions. This choice depends on properties specified by users or decision makers, the nature of the objects to aggregate as well as computational limitations due to prohibitive algorithmic complexity. This problem demands an exhaustive study of aggregation functions that requires an axiomatic treatment and classification of aggregation procedures as well as a deep understanding of their structural behavior. It also requires a representation formalism for knowledge, in our case decision rules, as well as methods for extracting them. Typical approaches include rough-set and FCA approaches, that we aim to extend in order to increase expressivity, applicability and readability of results. Direct applications of these efforts are expected in the context of two multidisciplinary projects, namely the “Fight Heart Failure” and the European H2020 “CrossCult” project.

In our recent work, we mainly focused on the utility-based preference model in which preferences are represented as an aggregation of preferences over different attributes, structured or not, both in the numerical and qualitative settings. In the latter case, we provided axiomatizations of noteworthy classes of lattice-based aggregation functions, which were then used to model preferences and to provide their logical description [14]. In this qualitative setting, we also tackled the problem of computing version spaces (with explicit descriptions of all models compatible with a given dataset) and proved a dichotomy theorem showing that the problem is NP-complete for preferences over at least 4 attributes whereas it is solvable in polynomial time otherwise [61].

Finding consensual structures among different classifications or metrics is again a challenging task, especially, for large and multi-source data, and its importance becomes apparent since algorithmic approaches are often heuristic on such datasets and they rarely produce the same output. The difficulty in extracting such consensual structures is then to find appropriate and meaningful aggregation rules, and their impossibility is often revealed by Arrow type impossibility results. In the current year, we focused on median structures [19], [21] that include several relational structures (trees, graphs, lattices) and allow several consensus procedures.

7.2. Knowledge Discovery in Healthcare and Life Sciences

Participants: Miguel Couceiro, Adrien Coulet, Kévin Dalleau, Joël Legrand, Pierre Monnin, Amedeo Napoli, Chedy Raïssi, Mohsen Sayed, Malika Smaïl-Tabbone, Yannick Toussaint.

Life Sciences constitute a challenging domain for KDDK. Biological data are complex from many points of views, e.g. voluminous, high-dimensional and deeply inter-connected. Analyzing such data is a crucial issue in healthcare, environment and agronomy. Besides, many bio-ontologies are available and can be used to enhance the knowledge discovery process. Accordingly, the research work of the Orpailleur team in KDDK applied to Life Sciences is in concern with mining biological data, data integration, information retrieval, and use of bio-ontologies and linked data for resource annotation.

7.2.1. Ontology-based Clustering of Biological Linked Open Data

Increasing amounts of biomedical data provided as Linked Open Data (LOD) offer novel opportunities for knowledge discovery in bio-medicine. We proposed an approach for selecting, integrating, and mining LOD with the goal of discovering genes responsible for a disease [88]. We are currently working on the integration of LOD about known phenotypes and genes responsible for diseases along with relevant bio-ontologies. We are also defining a corpus-based semantic distance. One possible application of this work is to build and compare possible diseaseomes, i.e. global graphs representing all diseases connected according to their pairwise similarity values.

7.2.2. Biological Data Aggregation for Knowledge Discovery

Two multi-disciplinary projects were initiated in 2016, in collaboration with the Capsid Team, with a group of clinicians from the Regional University Hospital (CHU Nancy) and bio-statisticians from the Maths Lab (IECL). The first project is entitled ITM2P [0] and depends on the so-called CPER 2015–2020 framework. We are involved in the design of the SMEC platform as a support for "Simulation, Modeling and Knowledge Extraction from Bio-Medical Data".

The second project is a RHU [0] project entitled *Fight Heart Failure* (FHF), where we are in charge of a workpackage about "data aggregation" mechanisms. Accordingly, we are working on the definition of multidimensional similarity measure for comparing and clustering sets of patients. Each cluster should correspond to a bioprofile, i.e. a subgroup of patients sharing the same form of the disease and thus the same diagnosis and care strategy.

The first results were presented at the International Symposium on Aggregation and Structures (ISAS 2016) [36]. We propose the GABS for "Graph Aggregation Based Similarity" approach for complex graph aggregation resulting in a similarity graph between a subset of nodes. Indeed the initial graph contains two types of nodes, i.e. individuals and attributes. The pairwise similarity between individuals is derived from the various paths in the initial graph. This setting allows the integration of domain knowledge in the initial graph (corresponding to domain ontologies, norms...). Another advantage of the GABS approach is to generate a similarity graph which can be used as input for various clustering algorithms (graph-based ones as well as those working on similarity/distance matrix).

[0]"Innovations Technologiques, Modélisation et Médecine Personnalisée"
[0]"Recherche Hospitalo-Universitaire"

The next question will be to build a prediction model for each bioprofile/subgroup (once validated by the clinicians) for a decision support system. Thus, we are investigating SRL ("Statistical Relational Learning") methods which combine symbolic and probabilistic methods for improving expressivity (through logical or relational languages) and for dealing with uncertainty.

7.2.3. Suggesting Valid Pharmacogenes by Mining Linked Open Data and Electronic Health Records

A standard task in pharmacogenomics research is identifying genes that may be involved in drug response variability and called "pharmacogenes". As genomic experiments in this domain tend to generate many false positives, computational approaches based on background knowledge may generate more valuable results. Until now, the later have only used molecular networks databases or biomedical literature. We are studying a new method taking advantage of various linked data sources to validate uncertain drug-gene relationships, i.e. pharmacogenes [75]. One advantage relies on the standard implementation of linked data that facilitates the joint use of various sources and makes easier the consideration of features of various origins. Accordingly, we selected, formatted, interconnected and published an initial set of linked data sources relevant to pharmacogenomics. We applied numerical classification methods for extracting drug-gene pairs that can become validated pharmacogene candidates.

The ANR project "PractiKPharma" initiated in 2016 relies on similar ideas, having the motivation of validating state-of-the-art knowledge in pharmacogenomics (http://practikpharma.loria.fr/). The originality of "PractiKPharma" is to use Electronic Health Records (EHRs) to constitute cohorts of patients that can be mined for validating extracted pharmacogenomics knowledge units.

7.2.4. Analysis of biomedical data annotated with ontologies

In the context of the Snowflake Inria Associate team, Gabin Personeni, who is a PhD student co-supervised by Marie-Dominique Devignes (Capsid EPI) and Adrien Coulet (Orpailleur EPI) spent four months at the Stanford University in 2016. After this internship, we developed an approach based on pattern structures to identify frequently associated ADRs (Adverse Drug Reactions) from patient data either in the form of EHR or ADR spontaneous reports [51], [49]. In this case, pattern structures provide an expressive representation of ADR, taking into account the multiplicity of drugs and phenotypes involved in such reactions. Additionally, pattern structures allow considering diverse biomedical ontologies used to represent or annotate patient data, enabling a "semantic" comparison of ADRs. Up to now, this is the first research work considering such representations to mine rules between frequently associated ADRs. We illustrated the generality of the approach on two distinct patient datasets, each of them linked to distinct biomedical ontologies. The first dataset corresponds to anonymized EHRs, extracted from "STRIDE", the EHR data warehouse of Stanford Hospital and Clinics. The second dataset is extracted from the U.S. FDA (for Food & Drug Administration) Adverse Event Reporting System (FAERS). Several significant association rules have been extracted and analyzed and may be used as a basis of a recommendation system.

7.3. Knowledge Engineering and Web of Data

Participants: Emmanuelle Gaillard, Nicolas Jay, Florence Le Ber, Jean Lieber, Amedeo Napoli, Emmanuel Nauer, Justine Reynaud.

Keywords: knowledge engineering, web of data, definition mining, classification-based reasoning, case-based reasoning, belief revision, semantic web

7.3.1. Around the Taaable Research Project

The Taaable project was originally created as a challenger of the Computer Cooking Contest (ICCBR Conference) [73]. Beyond its participation to the CCC challenges, the Taaable project aims at federating various research themes: case-based reasoning (CBR), information retrieval, knowledge acquisition and extraction, knowledge representation, belief change theory, ontology engineering, semantic wikis, text-mining, etc. CBR performs adaptation of recipes w.r.t. user constraints. The reasoning process is based on a cooking domain ontology (especially hierarchies of classes) and adaptation rules. The knowledge base is encoded within a semantic wiki containing the recipes, the domain ontology and adaptation rules.

As acquiring knowledge from experts is costly, a new approach was proposed to allow a CBR system using partially reliable, non expert, knowledge from the web for reasoning. This approach is based on notions such as belief, trust, reputation and quality, as well as their relationships and rules to manage the knowledge reliability. The reliability estimation is used to filter knowledge with high reliability as well as to rank the results produced by the CBR system. Performing CBR with knowledge resulting from an e-community is improved by taking into account the knowledge reliability [10]. In the same way, another study shows how the case retrieval of a CBR system can be improved using typicality. Typicality discriminates subclasses of a class in the domain ontology depending of how a subclass is a good example for its class. An approach has been proposed to partition the subclasses of some classes into atypical, normal and typical subclasses in order to refine the domain ontology. The refined ontology allows a finer-grained generalization of the query during the retrieval process, improving at the same time the final results of the CBR system.

The Taaable system also includes a module for adapting textual preparations (from a source recipe text to an adapted recipe text, through a formal representation in the qualitative algebra INDU). The evaluation of this module as a whole thanks to users has been carried out and has shown its efficiency (w.r.t. text quality and recipe quality), when compared with another approach to textual adaptation [76].

FCA allows the classification of objects according to the properties they share into a concept lattice. A lattice has been built on a large set a cooking recipes according to the ingredients they use, producing a hierarchy of ingredient combinations. When a recipe R has to be adapted, this lattice can be used to search the best ingredient combinations in the concepts that are the closest to the concept representing R.

Minimal change theory and belief revision can be used as tools to support adaptation in CBR, i.e. the source case is modified to be consistent with the target problem using a revision operator. Belief revision was applied to Taaable to adjust the ingredient quantities using specific inference engines.

Another approach to adaptation based on the principles of analogical transfer applied to the formalism RDFS has been developed [41]. It is based on the problem-solution dependency represented as an RDFS graph: this dependency within the source case is modified so that it fits the context of the target problem. The application problem that has guided this research addresses the issue of cocktail name adaptation: given a cocktail recipe, the name of this cocktail and the ingredient substitution that produces a new cocktail, how could the new cocktail be called?

7.3.2. Exploring and Classifying the Web of Data

A part of the research work in Knowledge Engineering is oriented towards knowledge discovery in the web of data, as, with the increased interest in machine processable data, more and more data is now published in RDF (Resource Description Framework) format. The popularization and quick growth of Linked Open Data (LOD) has led to challenging aspects regarding quality assessment and data exploration of the RDF triples that shape the LOD cloud. Particularly, we are interested in the completeness of the data and the their potential to provide concept definitions in terms of necessary and sufficient conditions [66]. We have proposed a novel technique based on Formal Concept Analysis which organizes subsets of RDF data into a concept lattice [43]. This allows data exploration as well as the discovery of implication rules which are used to automatically detect missing information and then to complete RDF data and to provide definitions. Moreover, this is also a way of reconciling syntax and semantics in the LOD cloud. Experiments on the DBpedia knowledge base shows that this kind of approach is well-founded and effective.

7.4. Advances in Graph Theory

Participants: Aurore Alcolei, Rémi de Joannis de Verclos, François Pirot, Jean-Sébastien Sereni.

Keywords: graph theory, graph coloring, extremal graph theory, chromatic number, two-mode data networks

Motivated by notions brought forward by sociology, we confirm a conjecture by Everett, Sinclair, and Dankelmann [Some Centrality results new and old, J. Math. Sociology 28 (2004), 215–227] regarding the problem of maximizing closeness centralization in two-mode data, where the number of data of each type is fixed. Intuitively, our result states that among all networks obtainable via two-mode data, the largest closeness is achieved by simply locally maximizing the closeness of a node. Mathematically, our study concerns bipartite graphs with fixed size bipartitions, and we show that the extremal configuration is a rooted tree of depth 2, where neighbors of the root have an equal or almost equal number of children [24].

Using recently introduced techniques based on entropy compression, we proved that the acyclic chromatic number of a graph with maximum degree Δ is less than $2.835\Delta^{4/3} + \Delta$. This improved the previous upper bound, which was $50\Delta^{4/3}$ (see [91] which is now published in Journal of Combinatorics, 7(4):725–737, 2016).

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. Hydreos

Participant: Jean-François Mari.

Hydreos is a state organization –actually a so-called “Pôle de compétitivité”– aimed at evaluating the delivering and the quality of water (http://www.hydreos.fr/fr). Actually, data about water resources rely on many agronomic variables, including land use successions. The data to be analyzed are obtained by surveys or by satellite images and describe the land use at the level of the agricultural parcel. Then there is a search for detecting changes in land use and for correlating these changes to groundwater quality. Accordingly, one main challenge in our participation in Hydreos is to process and analyze space-time data for reaching a better understanding of the changes in the organization of a territory. The systems ARPEnTAge and CarottAge (see § 6.2.1) are used in this context, especially by agronomists of INRA (ASTER Mirecourt http://www6.nancy.inra.fr/sad-aster).

8.2. National Initiatives

8.2.1. ANR

8.2.1.1. Hybride (2011-2016)

Participants: Adrien Coulet, Amedeo Napoli, Chedy Raïssi, My Thao Tang, Mohsen Sayed, Yannick Toussaint.

The Hybride research project (http://hybride.loria.fr/) aims at combining Natural Language Processing (NLP) and Knowledge Discovery in Databases (KDD) for text mining. A key idea is to design an interacting and convergent process where NLP methods are used for guiding text mining while KDD methods are used for guiding the analysis of textual documents. NLP methods are mainly based on text analysis and extraction of general and temporal information. KDD methods are based on pattern mining, e.g. patterns and sequences, formal concept analysis and graph mining. In this way, NLP methods applied to texts extract “textual information” that can be used by KDD methods as constraints for focusing the mining of textual data. By contrast, KDD methods extract patterns and sequences to be used for guiding information extraction from texts and text analysis. Experimental and validation parts associated with the Hybride project are provided by an application to the documentation of rare diseases in the context of Orphanet.

The partners of the Hybride consortium are the GREYC Caen laboratory (pattern mining, NLP, text mining), the MoDyCo Paris laboratory (NLP, linguistics), the INSERM Paris laboratory (Orphanet, ontology design), and the Orpailleur team at Inria NGE (FCA, knowledge representation, pattern mining, text mining). The Hybride project ended on 30th November 2016.

8.2.1.2. ISTEX (2014–2016)

Participant: Yannick Toussaint.

ISTEX is a so-called "Initiative d'excellence" managed by CNRS and DIST ("Direction de l'Information Scientifique et Technique"). ISTEX aims at giving to the research and teaching community an on-line access to scientific publications in all the domains (http://www.istex.fr/istex-excellence-initiative-of-scientific-and-technical-information/). Thus ISTEX requires a massive acquisition of documents such as journals, proceedings, corpus, databases...ISTEX-R is one research project within ISTEX in which the Orpailleur team is involved, with two other partners, namely ATILF laboratory and INIST Institute (both located in Nancy). ISTEX-R aims at developing new tools for querying full-text documentation, analyzing content and extracting information. A platform is under development to provide robust NLP tools for text processing, as well as methods in text mining and domain conceptualization.

8.2.1.3. PractiKPharma (2016–2020)

Participants: Adrien Coulet, Joël Legrand, Pierre Monnin, Amedeo Napoli, Malika Smaïl-Tabbone, Yannick Toussaint.

The ANR project PractiKPharma (http://practikpharma.loria.fr/) is interested in the validation of domain knowledge in pharmacogenomics. The originality of PractiKPharma is to use "Electronic Health Records" (EHRs) to constitute cohorts of patients, cohorts which are are then mined for validating extracted pharmacogenomics knowledge units after validation w.r.t. literature knowledge. This project involves two other labs, namely LIRMM at Montpellier and CRC Paris.

8.2.1.4. Termith (2014–2016)

Participant: Yannick Toussaint.

Termith (http://www.atilf.fr/ressources/termith/) is an ANR Project involving a series of laboratories, namely ATILF, INIST, Inria Nancy Grand Est, Inria Saclay, LIDILEM, and LINA. It aims at indexing documents belonging to different domain of Humanities. Thus, the project focuses on extracting candidate terms (information extraction) and on disambiguation.

In the Orpailleur team, we are mainly concerned by information extraction using Formal Concept Analysis techniques, but also pattern and sequence mining. The objective is to define contexts introducing terms, i.e. finding textual environments allowing a system to decide whether a textual element is actually a candidate term and its corresponding environment. This disambiguation process was described and published at LREC 2016 [35]. The Termith project ended in April 2016.

8.2.2. FUI POQEMON (2014-2016)

Participants: Chedy Raïssi, Mickaël Zehren.

The publication of transaction data, such as market basket data, medical records, and query logs, serves the public benefit. Mining such data allows the derivation of association rules that connect certain items to others with measurable confidence. Still, this type of data analysis poses a privacy threat; an adversary having partial information on a person's behavior may confidently associate that person to an item deemed to be sensitive. Ideally, an anonymization of such data should lead to an inference-proof version that prevents the association of individuals to sensitive items, while otherwise allowing truthful associations to be derived. The POQEMON project aims at developing new pattern mining methods and tools for supporting privacy preserving knowledge discovery from monitoring purposes on mobile phone networks. The main idea is to develop sound approaches that handle the tradeoff between privacy of data and the power of analysis. Original approaches to this problem were based on value perturbation, damaging data integrity. Recently, value generalization has been proposed as an alternative; still, approaches based on it have assumed either that all items are equally sensitive, or that some are sensitive and can be known to an adversary only by association, while others are non-sensitive and can be known directly. Yet in reality there is a distinction between sensitive and non-sensitive items, but an adversary may possess information on any of them. Most critically, no antecedent method aims at a clear inference-proof privacy guarantee. In this project, we integrated the ρ-uncertainty privacy concept that inherently safeguards against sensitive associations without constraining the nature of an adversary's knowledge and without falsifying data. The project integrates the ρ-uncertainty pattern mining approach with novel data visualization techniques.

The POQEMON research project (https://members.loria.fr/poqemon/) involves the following partners: Altran, DataPublica, GenyMobile, HEC, IP-Label, Next Interactive Media, Orange and Université Paris-Est Créteil, and Inria Nancy Grand Est.

8.2.3. CNRS PEPS and Mastodons projects

8.2.3.1. Mastodons HyQual (2016–2018)

Participants: Miguel Couceiro, Esther Galbrun, Dhouha Grissa, Amedeo Napoli, Chedy Raïssi, Justine Reynaud.

The HyQual project was proposed and initiated this year in the framework of the Mastodons CNRS Call about data quality in data mining (see http://www.cnrs.fr/mi/spip.php?article819&lang=fr). This project is interested in the mining of nutritional data for discovering predictive biomarkers of diabetes and metabolic syndrome in elder populations. The data mining methods which are considered here are hybrid, combining symbolic and numerical methods, and are applied to complex and noisy metabolic data [39]. In the HyQual project, we are mainly interested by the quality of the data at hand and the patterns that can be discovered. In particular, we check whether we can find possible definitions within the data (actually double implications) and redescriptions (under the form of different descriptions of the same data). In this way, we can study the definitional power of the data and as well the incompleteness of the data, leading to two original ways of considering data quality. The project involves researchers from the Orpailleur Team, with researchers from LIRIS Lyon, ICube Strasbourg, and INRA Clermont-Ferrand.

8.2.3.2. PEPS Confocal (2015–2016)

Participants: Adrien Coulet, Amedeo Napoli, Chedy Raïssi, Malika Smaïl-Tabbone.

The Confocal Project (see http://www.cnrs.fr/ins2i/spip.php?article1183) is interested in the design of new methods in bioinformatics for analyzing and classifying heterogeneous omics data w.r.t. biological domain knowledge. We are working on the adaption of FCA and pattern structures for discovering patterns and associations in gene data with the help of domain ontologies. One important objective of the project is to check whether such a line of research could be reused on so-called "discrete models in molecular biology".

8.2.3.3. PEPS Prefute (2015–2016)

Participants: Quentin Brabant, Adrien Coulet, Miguel Couceiro, Esther Galbrun, Amedeo Napoli, Chedy Raïssi, Justine Reynaud, Mohsen Sayed, Malika Smaïl-Tabbone, My Thao Tang, Yannick Toussaint.

The PEPS Prefute project is mainly interested in interaction and iteration in the knowledge discovery (KD) process. Usually the KD process is organized around three main steps which are (i) selection and preparation of the data, (ii) data mining, and (iii) interpretation of (selected) resulting patterns. An analyst, most of the time an expert of the data domain, is present for leading the KD process. Accordingly, the PEPS Prefute project is interested in the study of interactions between the analyst and the KD process, i.e. pushing constraints, preferences and domain knowledge, for guiding and improving the KD process. One possible way is to discover initial patterns acting as seeds for searching farther the pattern space w.r.t. this initial seeds possibly linked to preferences of the analyst. In this way, the interesting pattern space is much more concise and of much lower size.

Then, the importance of preferences and domain knowledge in interaction with KD, and as well, visualization tools, have to be improved for allowing work with large and complex datasets (see https://www.greyc.fr/fr/node/2207).

8.3. European Initiatives

8.3.1. FP7 & H2020 Projects

8.3.1.1. CrossCult (H2020 Project, 2016-2020)

Participants: Miguel Couceiro, Nyoman Juniarta, Amedeo Napoli, Chedy Raïssi.

CrossCult (http://www.crosscult.eu/) aims to make reflective history a reality in the European cultural context, by enabling the re-interpretation of European (hi)stories through cross-border interconnections among cultural digital resources, citizen viewpoints and physical venues. The project has two main goals. The first goal is to lower cultural EU barriers and create unique cross-border perspectives, by connecting existing digital historical resources and by creating new ones through the participation of the public. The second goal is to provide long-lasting experiences of social learning and entertainment that will help towards the better understanding and re-interpretation of European history. To achieve these goals, CrossCult will use cutting-edge technology to connect existing digital cultural assets and to combine them with interactive experiences that all together are intended to increase retention, stimulate reflection and help European citizens appreciate their past and present in a holistic manner. CrossCult will be implemented on 4 real-world flagship pilots involving a total of 8 sites across Europe.

The role of the Orpailleur Team (in conjunction with the Kiwi Team of LORIA) is mainly to work on the recommendation aspects, with a focus on defining an extended profile of the users and connecting these profiles with domain knowledge for leading the recommendation process [42].

The partners of the Orpailleur team in the CrossCult project are the following: Luxembourg Institute for Science and Technology and Centre Virtuel de la Connaissance sur l'Europe (Luxembourg, leader of the project), University College London (England), University of Malta (Malta), University of Peloponnese and Technological Educational Institute of Athens (Greece), Università degli Studi di Padova (Italy), University of Vigo (Spain), National Gallery (London, England), and GVAM Guìas Interactivas (Spain).

8.4. International Initiatives

8.4.1. Inria Associate Teams:SNOWFLAKE

8.4.1.1. SNOWFLAKE

Participants: Adrien Coulet, Joël Legrand, Pierre Monnin, Malika Smaïl-Tabbone.

Title: Knowledge Discovery from Linked Data and Clinical Notes

International Partner (Institution - Laboratory - Researcher):

Stanford (United States) - Department of Medicine, Stanford Center for Biomedical Informatics Research (BMIR) - Nigam Shah

Start year: 2014

Web site: http://snowflake.loria.fr/

Snowflake is an Inria Associate Team which started in 2014. It is aimed at facilitating the collaboration between researchers from the Inria Orpailleur team and the Stanford Center for Biomedical Informatics Research, Stanford University, USA. The main objective of Snowflake is to improve biomedical knowledge discovery by connecting Electronic Health Records (EHRs) with domain knowledge either in the form of ontologies or of Linked Open Data (LOD). Such a connection should help to complete domain knowledge w.r.t. EHRs. The initial focus of Snowflake is the identification and characterization of groups of patients w.r.t. (adverse) reactions to drugs. Identified features associated with such groups of patients could be used as predictors of over- or under-reactions to some drugs.

8.4.2. Participation in Other International Programs

8.4.2.1. A stay at NASA Frontier Development Lab

Participant: Chedy Raïssi.

In 2013, NASA presented the "Asteroid Grand Challenge", a White House supported initiative to supplement the NEO (Near-Earth Object) Program, with a mission: "Find all asteroid threats to human populations and to know what to do about them." There remain a number of unresolved gaps in this challenge, both in terms of discovery, characterization and eventual mitigation strategies, should a potentially hazardous asteroid (PHA) be discovered. By bringing new approaches in computer science, such as deep learning and data mining to tackle specific parts of the problem, solutions may be revealed that, combined with existing processes, significantly benefit the community as a whole.

In July 2016, Chedy Raïssi visited NASA Ames and SETI Institute as part of the Frontier Development Lab. He worked there on developing meaningful research opportunities, as well as support the work of the planetary defense community and show the potential of this kind of applied research methodology to deliver breakthrough of significant value. The work was over a period of six weeks, focusing on Delay-Doppler radar imaging. Delay-Doppler radar imaging is a powerful technique to characterize the trajectories, shapes, and spin states of near-Earth asteroids and has yielded detailed models of dozens of objects. Since the 1990s, Delay-Doppler data has been analyzed using the SHAPE software developed originally by Steven J. Ostro. SHAPE performs sequential single-parameter fitting, and requires considerable computation runtime and human intervention. Reconstructing asteroid shapes and spins from Delay-Doppler data is, like many inverse problems, computationally intensive and requires extensive human oversight of the shape modeling process. Chedy Raïssi has explored two new techniques to better automate Delay-Doppler shape modeling: Bayesian optimization and deep generative models.

8.4.2.2. Ciência Sem Fronteiras (2014–2016)

Participant: Amedeo Napoli.

Program "Ciência Sem Fronteiras" is a Brazilian research fellowship which provides a funding for the stay of a visiting French researcher in Brazil at Universidade Federal Pernambuco Recife for three years. The on-going project is called "Formal Concept Analysis as a Support for Knowledge Discovery" and is aimed at combining FCA methods with numerical clustering methods used by Brazilian colleagues. This project is supervised in Brazil by Professor Francisco de A.T. de Carvalho (CIn/UFPE).

The project aims at developing and comparing classification and clustering algorithms for complex data (especially interval and multi-valued data). Two families of algorithms are studied, namely "clustering algorithms" based on the use of a similarity or a distance for comparing the objects, and "classification algorithms in Formal Concept Analysis (FCA)" based on attribute sharing between objects. The objectives here are to combine the facilities of both families of algorithms for improving the potential of each family in dealing with more complex and voluminous datasets.

8.4.2.3. STIC AmSud: Autonomic Knowledge Discovery (AKD, 2015–2016)

Participants: Miguel Couceiro, Esther Galbrun, Amedeo Napoli, Chedy Raïssi.

This research project involves researchers with different specialties, from Brazil (Universidade Federal Rio Grande do Sul), from Chile (UFSM Santiago and Valparaiso), from Uruguay (Universidad de la Repùblica), and the Orpailleur Team. The project is interested in the design of solutions able to proactively understand the behavior of systems and networks in order to prevent vulnerable states. Accordingly, we aim at integrating knowledge discovery techniques within autonomic systems in order to provide intelligent self-configuration and self-protection mechanisms. The results of this project may not only benefit to end-users but also highly contribute to the scientific community by providing solid foundations for the development of more secure, scalable, and reliable management approaches.

8.4.2.4. LEA STRUCO

Participant: Jean-Sébastien Sereni.

LEA STRUCO is an “Associated International Laboratory” of CNRS between IÚUK, Prague, and LIAFA, Paris. It focuses on high-level study of fundamental combinatorial objects, with a particular emphasis on comprehending and disseminating the state-of-the-art theories and techniques developed. The obtained insights shall be applied to obtain new results on existing problems as well as to identify directions and questions for future work. Jean-Sébastien Sereni is the contact person for LEA STRUCO which was initiated when Jean-Sébastien was a member of LIAFA.

8.4.2.5. Research Collaboration with HSE Moscow

Participants: Miguel Couceiro, Adrien Coulet, Amedeo Napoli, Chedy Raïssi, Justine Reynaud.

An on-going collaboration involves the Orpailleur team and Sergei O. Kuznetsov at Higher School of Economics in Moscow (HSE). Amedeo Napoli visited HSE laboratory several times while Sergei O. Kuznetsov visited Inria Nancy Grand Est several times too. The collaboration is materialized by the joint supervision of students (such as for example the thesis of Aleksey Buzmakov defended at the end of 2015), and the the organization of scientific events, as in particular the workshop FCA4AI whose fifth edition was organized this year in August at ECAI 2016 (see http://www.fca4ai.hse.ru) [53]. A special session about Knowledge Discovery and Formal Concept Analysis will be supervised by Sergei O. Kuznetsov and Amedeo Napoli at the next ISMIS Conference in Warsaw (Poland) next June 2017 (http://ismis2017.ii.pw.edu.pl/s_kd_fca.php).

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organization, General Chairs, Scientific Chairs

- “FCA4AI 2016”. Amedeo Napoli organized with Sergei O. Kuznetsov (HSE Moscow) and Sebastian Rudolph (TU Dresden) the fifth workshop FCA4AI (“What can do FCA for Artificial Intelligence”) which was associated with the ECAI Conference in The Hague (Netherlands, August 2016, see http://www.fca4ai.hse.ru/2016 and http://ceur-ws.org/Vol-1703) [53].

9.1.1.1. Scientific Animation

- The scientific animation in the Orpailleur team is based on the Team Seminar which is called the “Malotec” seminar (http://malotec.loria.fr/?p=1). The Malotec seminar is held in general twice a month and is used either for general presentations of members of the team or for invited presentations of external researchers.
- Members of the Orpailleur team are all involved, as members or as head persons, in various national research groups.
- The members of the Orpailleur team are involved in the organization of conferences and workshops, as members of conference program committees (ECAI, ECML-PKDD, ICCBR, ICDM, ICFCA, IJCAI, KDD...), as members of editorial boards, and finally in the organization of journal special issues.

9.2. Teaching – Supervision – Juries

- The members of the Orpailleur team are involved in teaching at all levels of teaching, mainly at University of Lorraine. Actually, most of the members of the Orpailleur team are employed on “Université de Lorraine” positions.
- The members of the Orpailleur team are also involved in student supervision, at all university levels, from under-graduate until post-graduate students.

- Finally, the members of the Orpailleur team are involved in HDR and thesis defenses, being thesis referees or thesis committee members.

10. Bibliography

Major publications by the team in recent years

[1] E. BRESSO, R. GRISONI, G. MARCHETTI, A.-S. KARABOGA, M. SOUCHET, M.-D. DEVIGNES, M. SMAÏL-TABBONE.*Integrative relational machine-learning for understanding drug side-effect profiles*, in "BMC Bioinformatics", 2013, vol. 14, n^{o} 1, 207 [*DOI :* 10.1186/1471-2105-14-207], https://hal.inria.fr/hal-00843914.

[2] M. COUCEIRO, D. DUBOIS, H. PRADE, T. WALDHAUSER.*Decision-making with Sugeno integrals: Bridging the gap between multicriteria evaluation and decision under uncertainty*, in "Order", 2016, vol. 33, n^{o} 3, p. 517-535 [*DOI :* 10.1007/S11083-015-9382-8], https://hal.archives-ouvertes.fr/hal-01184340.

[3] K. DALLEAU, N. COUMBA NDIAYE, A. COULET.*Suggesting valid pharmacogenes by mining linked data*, in "Semantic Web Applications and Tools for Life Sciences (SWAT4LS) 2015", Cambridge, United Kingdom, Proceedings of the Semantic Web Applications and Tools for Life Sciences (SWAT4LS) 2015, December 2015, https://hal.inria.fr/hal-01239568.

[4] V. DUFOUR-LUSSIER, F. LE BER, J. LIEBER, L. MARTIN.*Case Adaptation with Qualitative Algebras*, in "International Joint Conferences on Artificial Intelligence", Pékin, China, F. ROSSI (editor), Proceedings of the Twenty-Third International Joint Conference on Artificial Intelligence, AAAI Press, August 2013, p. 3002-3006, https://hal.inria.fr/hal-00871703.

[5] Z. DVOŘÁK, J.-S. SERENI, J. VOLEC.*Subcubic triangle-free graphs have fractional chromatic number at most* $14/5$, in "Journal of the London Mathematical Society", June 2014, vol. 89, n^{o} 3, p. 641–662, https://hal.archives-ouvertes.fr/hal-00779634.

[6] E. EGHO, C. RAÏSSI, T. CALDERS, N. JAY, A. NAPOLI.*On measuring similarity for sequences of itemsets*, in "Data Mining and Knowledge Discovery", May 2015, vol. 29, n^{o} 3, 33 [*DOI :* 10.1007/S10618-014-0362-1], https://hal.inria.fr/hal-01094383.

[7] E. GALBRUN, A. GIONIS, N. TATTI.*Top-k overlapping densest subgraphs*, in "Data Mining and Knowledge Discovery", September 2016, vol. 30, n^{o} 5, p. 1134 - 1165 [*DOI :* 10.1007/S10618-016-0464-Z], https://hal.archives-ouvertes.fr/hal-01399184.

[8] M. KAYTOUE, V. CODOCEDO, A. BUZMAKOV, J. BAIXERIES, S. O. KUZNETSOV, A. NAPOLI.*Pattern Structures and Concept Lattices for Data Mining and Knowledge Processing*, in "Machine Learning and Knowledge Discovery in Databases", Porto, Portugal, A. BIFET, M. MAY, B. ZADROZNY, R. GAVALDA, D. PEDRESCHI, F. BONCHI, J. CARDOSO, M. SPILIOPOULOU (editors), Lecture Notes in Computer Science, Springer International Publishing, 2015, vol. 9286, p. 227-231 [*DOI :* 10.1007/978-3-319-23461-8_19], https://hal.archives-ouvertes.fr/hal-01188637.

[9] J.-F. MARI, E.-G. LAZRAK, M. BENOÎT.*Time space stochastic modelling of agricultural landscapes for environmental issues*, in "Environmental Modelling and Software", March 2013, vol. 46, p. 219-227 [*DOI :* 10.1016/J.ENVSOFT.2013.03.014], https://hal.inria.fr/hal-00807178.

Publications of the year

Doctoral Dissertations and Habilitation Theses

[10] E. GAILLARD.*Managing and exploiting knowledge produced by an e-community – Application to case-based reasoning*, Université de Lorraine, CNRS, Inria, LORIA, UMR 7503, June 2016, https://hal.inria.fr/tel-01415288.

[11] M. T. TANG.*An Interactive and Iterative Knowledge Extraction Process Using Formal Concept Analysis*, Université de lorraine, June 2016, https://hal.inria.fr/tel-01425357.

Articles in International Peer-Reviewed Journal

[12] J. ALMEIDA, M. COUCEIRO, T. WALDHAUSER.*On the topological semigroup of equational classes of finite functions under composition*, in "Journal of Multiple-Valued Logic and Soft Computing", 2016, 24, https://hal.archives-ouvertes.fr/hal-01090645.

[13] A. BUZMAKOV, E. EGHO, N. JAY, S. O. KUZNETSOV, A. NAPOLI, C. RAÏSSI.*On Mining Complex Sequential Data by Means of FCA and Pattern Structures*, in "Int. J. Gen. Syst.", 2016, vol. 45, n° 2, p. 135-159 [*DOI :* 10.1080/03081079.2015.1072925], https://hal.archives-ouvertes.fr/hal-01186715.

[14] M. COUCEIRO, D. DUBOIS, H. PRADE, T. WALDHAUSER.*Decision-making with sugeno integrals: Bridging the gap between multicriteria evaluation and decision under uncertainty*, in "Order", 2016, vol. 33, n° 3, p. 517-535 [*DOI :* 10.1007/s11083-015-9382-8], https://hal.archives-ouvertes.fr/hal-01184340.

[15] M. COUCEIRO, L. HADDAD, I. G. ROSENBERG.*Partial clones containing all Boolean monotone self-dual partial functions*, in "Journal of Multiple-Valued Logic and Soft Computing", 2016, vol. 27, n° 2-3, p. 183-192, https://hal.archives-ouvertes.fr/hal-01093942.

[16] M. COUCEIRO, L. HADDAD, K. SCHÖLZEL, T. WALDHAUSER.*A Solution to a Problem of D. Lau: Complete Classification of Intervals in the Lattice of Partial Boolean Clones*, in "Journal of Multiple-Valued Logic and Soft Computing", 2016, 8, https://hal.inria.fr/hal-01183004.

[17] M. COUCEIRO, L. HADDAD, K. SCHÖLZEL, T. WALDHAUSER.*On the interval of strong partial clones of Boolean functions containing Pol((0,0), (0,1), (1,0))*, in "Algebra Universalis", 2016, https://hal.inria.fr/hal-01404588.

[18] M. COUCEIRO, E. LEHTONEN.*On the arity gap of finite functions : results and applications.*, in "Journal of Multiple-Valued Logic and Soft Computing", 2016, vol. 27, n° 1-2, 15, https://hal.inria.fr/hal-01175695.

[19] M. COUCEIRO, J.-L. MARICHAL, B. TEHEUX.*Conservative Median Algebras and Semilattices*, in "Order", March 2016, vol. 33, n° 1, p. 121-132 [*DOI :* 10.1007/s11083-015-9356-x], https://hal.inria.fr/hal-01175696.

[20] M. COUCEIRO, J.-L. MARICHAL, B. TEHEUX.*Relaxations of associativity and preassociativity for variadic functions*, in "Fuzzy Sets and Systems", 2016, vol. 229, p. 89-97, https://hal.archives-ouvertes.fr/hal-01184334.

[21] M. COUCEIRO, G. MELETIOU.*On a special class of median algebras*, in "Miskolc Mathematical Notes", 2016, https://hal.inria.fr/hal-01248142.

[22] E. GALBRUN, A. GIONIS, N. TATTI.*Top-k overlapping densest subgraphs*, in "Data Mining and Knowledge Discovery", September 2016, vol. 30, n^o 5, p. 1134 - 1165 [*DOI :* 10.1007/S10618-016-0464-Z], https://hal.archives-ouvertes.fr/hal-01399184.

[23] D. GRISSA, M. PÉTÉRA, M. BRANDOLINI, A. NAPOLI, B. COMTE, E. PUJOS-GUILLOT.*Feature Selection Methods for Early Predictive Biomarker Discovery Using Untargeted Metabolomic Data*, in "Frontiers in Molecular Biosciences", June 2016, vol. 3, 15 [*DOI :* 10.3389/FMOLB.2016.00030], https://hal.archives-ouvertes.fr/hal-01421002.

[24] M. KRNC, J.-S. SERENI, R. SKREKOVSKI, Z. YILMA.*Closeness Centralization Measure for Two-mode Data of Prescribed Sizes*, in "Network Science", 2016, https://hal.inria.fr/hal-01289470.

[25] J.-S. SERENI, J. VOLEC.*A note on acyclic vertex-colorings*, in "Journal of Combinatorics", September 2016, vol. 7, n^o 4, p. 725–737, https://hal.archives-ouvertes.fr/hal-00921122.

International Conferences with Proceedings

[26] Y. ABID, A. IMINE, A. NAPOLI, C. RAÏSSI, M. RUSINOWITCH.*Online link disclosure strategies for social networks*, in "The 11th International Conference on Risks and Security of Internet and Systems", Roscoff, France, The 11th International Conference on Risks and Security of Internet and Systems, September 2016, https://hal.inria.fr/hal-01402062.

[27] M. ALAM, T. N. N. LE, A. NAPOLI.*Interactive Exploration over Concept Lattices with LatViz*, in "European Conference on Artificial Intelligence, Software Demo Track.", The Hague, Netherlands, August 2016, https://hal.inria.fr/hal-01420752.

[28] M. ALAM, T. N. N. LE, A. NAPOLI.*LatViz: A New Practical Tool for Performing Interactive Exploration over Concept Lattices*, in "CLA 2016 - Thirteenth International Conference on Concept Lattices and Their Applications", Moscow, Russia, July 2016, https://hal.inria.fr/hal-01420751.

[29] M. ALAM, T. N. N. LE, A. NAPOLI.*Steps Towards Interactive Formal Concept Analysis with LatViz*, in "Proceedings of the 5th International Workshop "What can FCA do for Artificial Intelligence"? co-located with the European Conference on Artificial Intelligence ECAI 2016", The Hague, Netherlands, August 2016, https://hal.inria.fr/hal-01420753.

[30] A. BUZMAKOV, A. NAPOLI.*How Fuzzy FCA and Pattern Structures are connected?*, in "5th Workshop "What can FCA do for Artificial Intelligence?" (FCA4AI'2016)", The Hague, Netherlands, August 2016, https://hal.inria.fr/hal-01420997.

[31] A. BUZMAKOV, A. NAPOLI.*On Scaling of Fuzzy FCA to Pattern Structures*, in "The 13th International Conference on Concept Lattices and their Applications (CLA2016)", Moscow, Russia, July 2016, https://hal.inria.fr/hal-01421000.

[32] C. CHAMARD-JOVENIN, A. CHESNEL, E. BRESSO, C. MOREL, C. THIÉBAUT, M. SMAÏL-TABBONE, E.-H. DJERMOUNE, M.-D. DEVIGNES, T. BOUKHOBZA, H. DUMOND.*Transgenerational effects of ERalpha36 over-expression on mammary gland development and molecular phenotype: clinical perspective for breast*

cancer risk and therapy., in "21st World Congress on Advances in Oncology and 19th International Symposium on Molecular Medicine", Athens, Greece, October 2016, https://hal.archives-ouvertes.fr/hal-01416469.

[33] *Best Paper*
V. CODOCEDO, J. BAIXERIES, M. KAYTOUE, A. NAPOLI.*Characterization of Order-like Dependencies with Formal Concept Analysis*, in "Thirteenth International Conference on Concept Lattices and Their Applications (CLA 2016)", Moscou, Russia, M. HUCHARD, S. O. KUZNETSOV (editors), CEUR-WS.org, July 2016, vol. 1624, p. 123-134, https://hal.archives-ouvertes.fr/hal-01348496.

[34] V. CODOCEDO, J. BAIXERIES, M. KAYTOUE, A. NAPOLI.*Contributions to the Formalization of Order-like Dependencies using FCA*, in "What can FCA do for Artificial Intelligence?", The Hague, Netherlands, August 2016, https://hal.inria.fr/hal-01420630.

[35] B. DAILLE, E. JACQUEY, G. LEJEUNE, L. F. MELO, Y. TOUSSAINT.*Ambiguity Diagnosis for Terms in Digital Humanities*, in "Language Resources and Evaluation Conference", Portorož, Slovenia, May 2016, https://hal.inria.fr/hal-01423650.

[36] K. DALLEAU, M. COUCEIRO, M.-D. DEVIGNES, C. RAÏSSI, M. SMAÏL-TABBONE.*Using aggregation functions on structured data: a use case in the FIGHT-HF project*, in "International Symposium on Aggregation and Structures (ISAS 2016)", Luxembourg, Luxembourg, G. KISS, J.-L. MARICHAL, B. TEHEUX (editors), International Symposium on Aggregation and Structures (ISAS 2016) - Book of abstracts, July 2016, https://hal.inria.fr/hal-01399232.

[37] D. GRISSA, B. COMTE, E. PUJOS-GUILLOT, A. NAPOLI.*A Hybrid Approach for Mining Metabolomic Data*, in "FCA4AI@ECAI 2016", La Haye, Netherlands, Proceedings of the 5th International Workshop "What can FCA do for Artificial Intelligence"? co-located with the European Conference on Artificial Intelligence, FCA4AI@ECAI 2016, CEUR-WS.org, August 2016, vol. 1703, https://hal.archives-ouvertes.fr/hal-01422050.

[38] D. GRISSA, B. COMTE, E. PUJOS-GUILLOT, A. NAPOLI.*A Hybrid Data Mining Approach for the Identification of Biomarkers in Metabolomic Data*, in "Concept Lattices and Their Applications", Moscou, Russia, Proceedings of the Thirteenth International Conference on Concept Lattices and Their Applications, Moscow, Russia, July 18-22, 2016, CEUR-WS.org, July 2016, vol. 1624, https://hal.archives-ouvertes.fr/hal-01421015.

[39] D. GRISSA, B. COMTE, E. PUJOS-GUILLOT, A. NAPOLI.*A Hybrid Knowledge Discovery Approach for Mining Predictive Biomarkers in Metabolomic Data*, in "ECML PKDD", Riva del garda, Italy, September 2016, p. 572 - 587 [*DOI :* 10.1007/978-3-319-46128-1_36], https://hal.archives-ouvertes.fr/hal-01421011.

[40] J. KALOFOLIAS, E. GALBRUN, P. MIETTINEN.*From Sets of Good Redescriptions to Good Sets of Redescriptions*, in "Proceedings of the 16th IEEE International Conference on Data Mining, ICDM'16", Barcelona, Spain, December 2016, https://hal.archives-ouvertes.fr/hal-01399294.

[41] N. KIANI, J. LIEBER, E. NAUER, J. SCHNEIDER.*Analogical Transfer in RDFS, Application to Cocktail Name Adaptation*, in "International Conference on Case-Based Reasoning (ICCBR-2016)", Atlanta, United States, A. GOEL, M. B. DIAZ-AGUDO, T. ROTH-BERGHOFER (editors), Case-Based Reasoning Research and Development, 24th International Conference, ICCBR 2016, Springer, October 2016, vol. 9969, p. 218 - 233 [*DOI :* 10.1007/978-3-319-47096-2_15], https://hal.inria.fr/hal-01410237.

[42] P.-E. OSCHE, S. CASTAGNOS, A. NAPOLI, Y. NAUDET.*Walk the line: Toward an efficient user model for recommendations in museums*, in "11th International Workshop on Semantic and Social Media Adaptation and Personalization (SMAP 2016)", Thessaloniki, Greece, October 2016, p. 83 - 88 [*DOI :* 10.1109/SMAP.2016.7753389], https://hal.inria.fr/hal-01421548.

[43] J. REYNAUD, Y. TOUSSAINT, A. NAPOLI.*Contribution to the Classification of Web of Data based on Formal Concept Analysis*, in "What can FCA do for Artificial Intelligence (FCA4AI) (ECAI 2016)", La Haye, Netherlands, August 2016, https://hal.inria.fr/hal-01420466.

[44] M. T. TANG, A. BUZMAKOV, Y. TOUSSAINT, A. NAPOLI.*Building a Domain Knowledge Model Based on a Concept Lattice Integrating Expert Constraints*, in "Proceedings of the Thirteenth International Conference on Concept Lattices and Their Applications", Moscow, Russia, July 2016, vol. 1624, p. 349–362, https://hal.inria.fr/hal-01400452.

National Conferences with Proceeding

[45] Q. BRABANT, M. COUCEIRO.*Apprentissage d'intégrales de Sugeno à partir de données inconsistantes*, in "25èmes Rencontre Francophone sur la Logique Floue et ses Applications", La Rochelle, France, 25èmes Rencontres Francophones sur la Logique Floue et ses Applications, November 2016, p. 49-56, https://hal.archives-ouvertes.fr/hal-01404567.

[46] Q. BRABANT, M. COUCEIRO, F. LABERNIA, A. NAPOLI.*Une approche de réduction de dimensionnalité pour l'agrégation de préférences qualitatives*, in "16ème Journées Francophones Extraction et Gestion des Connaissances, EGC 2016", Reims, France, January 2016, p. 345-350, https://hal.inria.fr/hal-01404913.

[47] C. CHAMARD-JOVENIN, A. CHESNEL, C. MOREL, M.-D. DEVIGNES, M. SMAÏL-TABBONE, T. BOUKHOBZA, H. DUMOND.*Long chain alkylphenol mixture promotes breast cancer initiation and progression through an ERα36-mediated mechanism*, in "2nd French Workshop on Endocrine disruption in wildlife and human health", Paris, France, January 2016, Présentation Poster, https://hal.archives-ouvertes.fr/hal-01320688.

[48] S. DA SILVA, F. LE BER, C. LAVIGNE.*Structures de haies dans un paysage agricole : une étude par chemin de Hilbert adaptatif et chaînes de Markov* , in "EGC 2016 – 16èemes Journées Francophones "Extraction et Gestion des Connaissances"", Reims, France, Revue des Nouvelles Technologies de l'Information, January 2016, vol. RNTI-E-30, p. 279–290, https://hal.archives-ouvertes.fr/hal-01266344.

[49] G. PERSONENI, M.-D. DEVIGNES, M. DUMONTIER, M. SMAÏL-TABBONE, A. COULET.*Extraction d'association d'EIM à partir de dossiers patients : expérimentation avec les structures de patrons et les ontologies*, in "Deuxième Atelier sur l'Intelligence Artificielle et la Santé", Montpellier, France, Atelier IA & Santé, June 2016, https://hal.inria.fr/hal-01391172.

Conferences without Proceedings

[50] E. GALBRUN, P. MIETTINEN.*Analysing Political Opinions Using Redescription Mining*, in "Proceedings of the Data Mining in Politics worshop at ICDM 2016, DMiP'16", Barcelona, Spain, December 2016, https://hal.archives-ouvertes.fr/hal-01399254.

[51] G. PERSONENI, M.-D. DEVIGNES, M. DUMONTIER, M. SMAÏL-TABBONE, A. COULET.*Discovering ADE associations from EHRs using pattern structures and ontologies*, in "Phenotype Day, Bio-Ontologies SIG, ISMB", Orlando, United States, July 2016, https://hal.inria.fr/hal-01369448.

Scientific Books (or Scientific Book chapters)

[52] A. W. GHOORAH, M.-D. DEVIGNES, M. SMAÏL-TABBONE, D. RITCHIE.*Classification and Exploration of 3D Protein Domain Interactions Using Kbdock*, in "Data Mining Techniques for the Life Sciences", O. CARUGO, F. EISENHABER (editors), Methods in Molecular Biology, Springer Science+Business Media New York, 2016, vol. 1415, p. 91-105 [*DOI :* 10.1007/978-1-4939-3572-7_5], https://hal.inria.fr/hal-01317448.

Books or Proceedings Editing

[53] S. O. KUZNETSOV, A. NAPOLI, S. RUDOLPH (editors). *Proceedings of the 5th International Workshop "What can FCA do for Artificial Intelligence?", FCA4AI 2016(co-located with ECAI 2016, The Hague, Netherlands, August 30th 2016)*, CEUR Workshop Proceedings, CEUR-WS.org, The Hague, Netherlands, 2016, vol. 1703, 135, https://hal.inria.fr/hal-01425672.

Research Reports

[54] K. EDWARDS, A. GIRÃO, J. VAN DEN HEUVEL, R. J. KANG, G. J. PULEO, J.-S. SERENI.*Extension from Precoloured Sets of Edges*, Loria & Inria Grand Est, 2016, https://hal.archives-ouvertes.fr/hal-01024843.

Scientific Popularization

[55] A. COULET, M. SMAÏL-TABBONE.*Mining Electronic Health Records to Validate Knowledge in Pharmacogenomics*, in "ERCIM News", January 2016, n° 104, 56, https://hal.inria.fr/hal-01369501.

[56] M.-D. DEVIGNES, M. SMAÏL-TABBONE, D. RITCHIE.*Kbdock - Searching and organising the structural space of protein-protein interactions*, in "ERCIM News", January 2016, n° 104, p. 24-25, https://hal.inria.fr/hal-01258117.

Other Publications

[57] Y. ABID, A. IMINE, A. NAPOLI, C. RAÏSSI, M. RIGOLOT, M. RUSINOWITCH.*Analyse d'activité et exposition de la vie privée sur les médias sociaux*, January 2016, 16ème conférence francophone sur l'Extraction et la Gestion des Connaissances (EGC 2016), Poster, https://hal.inria.fr/hal-01241619.

[58] G. BOSC, J.-F. BOULICAUT, C. RAÏSSI, M. KAYTOUE.*Anytime Discovery of a Diverse Set of Patterns with Monte Carlo Tree Search*, December 2016, working paper or preprint, https://hal.inria.fr/hal-01418663.

[59] M. COUCEIRO, M. GRABISCH.*On integer-valued means and the symmetric maximum*, September 2016, Documents de travail du Centre d'Economie de la Sorbonne 2016.80 - ISSN : 1955-611X, https://halshs.archives-ouvertes.fr/halshs-01412025.

[60] M. COUCEIRO, M. GRABISCH.*On integer-valued means and the symmetric maximum*, 2016, working paper or preprint, https://hal.inria.fr/hal-01404593.

[61] M. COUCEIRO, M. MARÓTI, T. WALDHAUSER, L. ZADORI.*Computing version spaces in the qualitative approach to multicriteria decision aid* , 2016, working paper or preprint, https://hal.inria.fr/hal-01404590.

[62] D. GRISSA, B. COMTE, E. PUJOS-GUILLOT, A. NAPOLI.*Combinaison de méthodes numériques et symboliques pour l'analyse de données métabolomiques*, 16ème Journées Francophones Extraction et Gestion des

Connaissances, EGC 2016, 18-22 Janvier 2016, Reims, France, Hermann-Editions, January 2016, vol. E-30, p. 555–556, Extraction et Gestion des Connaissances, Poster, https://hal.archives-ouvertes.fr/hal-01421035.

[63] J.-F. MARI, A. NAPOLI.*Maîtriser la complexité des systèmes: apport de la fouille de données*, November 2016, Cet exposé présente les travaux du projet Orpailleur en matière de fouille de données en agriculture numérique, https://hal.inria.fr/hal-01414117.

[64] J. REYNAUD, Y. TOUSSAINT, A. NAPOLI.*Analyse de concepts formels pour la classification de triplets RDF*, November 2016, Gestion de Données — Principes, Technologies et Applications (BDA 2016), Poster, https://hal.archives-ouvertes.fr/hal-01420737.

References in notes

[65] F. BAADER, D. CALVANESE, D. MCGUINNESS, D. NARDI, P. PATEL-SCHNEIDER (editors). *The Description Logic Handbook*, Cambridge University Press, Cambridge, UK, 2003.

[66] M. ALAM, A. BUZMAKOV, V. CODOCEDO, A. NAPOLI.*Mining Definitions from RDF Annotations Using Formal Concept Analysis*, in "International Joint Conference in Artificial Intelligence", Buenos Aires, Argentina, Proceedings of the Twenty-Fourth International Joint Conference on Artificial Intelligence, July 2015, https://hal.archives-ouvertes.fr/hal-01186204.

[67] M. ALAM, A. BUZMAKOV, A. NAPOLI, A. SAILANBAYEV.*Revisiting Pattern Structures for Structured Attribute Sets*, in "Proceedings of the Twelfth International Conference on Concept Lattices and Their Applications Clermont-Ferrand, France, October 13-16, 2015.", Clermont-Ferrand, France, CEUR Workshop Proceedings, August 2015, vol. 1466, p. 241-252, https://hal.inria.fr/hal-01186339.

[68] M. BARBUT, B. MONJARDET.*Ordre et classification – Algèbre et combinatoire (2 tomes)*, Hachette, Paris, 1970.

[69] O. BRUNEAU, S. GARLATTI, M. GUEDJ, S. LAUBÉ, J. LIEBER.*SemanticHPST: Applying Semantic Web Principles and Technologies to the History and Philosophy of Science and Technology*, in "The Semantic Web: ESWC 2015 Satellite Events", Portoroz, Slovenia, F. GANDON, A. ZIMMERMANN, C. FARON-ZUCKER, J. BRESLIN, S. VILLATA, C. GUÉRET (editors), Lecture Notes in Computer Science, Springer International Publishing, May 2015, vol. 9341, p. 416-427 [*DOI :* 10.1007/978-3-319-25639-9_53], https://hal.archives-ouvertes.fr/hal-01214698.

[70] A. BUZMAKOV, S. O. KUZNETSOV, A. NAPOLI.*Fast Generation of Best Interval Patterns for Nonmonotonic Constraints*, in "Machine Learning and Knowledge Discovery in Databases", Porto, Portugal, Lecture Notes in Computer Science, September 2015, vol. 9285, p. 157-172 [*DOI :* 10.1007/978-3-319-23525-7_10], https://hal.archives-ouvertes.fr/hal-01186718.

[71] V. CODOCEDO, A. NAPOLI.*A Proposition for Combining Pattern Structures and Relational Concept Analysis*, in "Formal Concept Analysis - 12th International Conference, ICFCA 2014, Cluj-Napoca, Romania, June 10-13, 2014. Proceedings", Cluj-Napoca, Romania, June 2014, p. 96 - 111 [*DOI :* 10.1007/978-3-319-07248-7_8], https://hal.inria.fr/hal-01095870.

[72] V. CODOCEDO, A. NAPOLI.*Formal Concept Analysis and Information Retrieval – A Survey*, in "International Conference in Formal Concept Analysis - ICFCA 2015", Nerja, Spain, J. BAIXERIES, C. SACAREA, M. OJEDA-ACIEGO (editors), Formal Concept Analysis - Lecture Notes in Computer Science, Springer, June

2015, vol. 9113, p. 61-77 [*DOI :* 10.1007/978-3-319-19545-2_4], https://hal.archives-ouvertes.fr/hal-01186196.

[73] A. CORDIER, V. DUFOUR-LUSSIER, J. LIEBER, E. NAUER, F. BADRA, J. COJAN, E. GAILLARD, L. INFANTE-BLANCO, P. MOLLI, A. NAPOLI, H. SKAF-MOLLI.*Taaable: a Case-Based System for personalized Cooking*, in "Successful Case-based Reasoning Applications-2", S. MONTANI, L. C. JAIN (editors), Studies in Computational Intelligence, Springer, January 2014, vol. 494, p. 121-162 [*DOI :* 10.1007/978-3-642-38736-4_7], https://hal.inria.fr/hal-00912767.

[74] S. DA SILVA.*Spatial data mining and modelling of hedgrows in agricultural landscapes*, Université de Lorraine, September 2014, https://hal.inria.fr/tel-01101424.

[75] K. DALLEAU, N. COUMBA NDIAYE, A. COULET.*Suggesting valid pharmacogenes by mining linked data*, in "Semantic Web Applications and Tools for Life Sciences (SWAT4LS) 2015", Cambridge, United Kingdom, Proceedings of the Semantic Web Applications and Tools for Life Sciences (SWAT4LS) 2015, December 2015, https://hal.inria.fr/hal-01239568.

[76] V. DUFOUR-LUSSIER, J. LIEBER.*Evaluating a textual adaptation system*, in "International Conference on Case-Based Reasoning", Frankfurt, Germany, September 2015, https://hal.inria.fr/hal-01178331.

[77] W. DUIVESTEIJN, A. FEELDERS, A. J. KNOBBE.*Exceptional Model Mining - Supervised descriptive local pattern mining with complex target concepts*, in "Data Mining and Knowledge Discovery", 2016, vol. 30, n^{o} 1, p. 47–98, http://dx.doi.org/10.1007/s10618-015-0403-4.

[78] R. FELDMAN, J. SANGER.*The Text Mining Handbook (Advanced Approaches in Analyzing Unstructured Data)*, Cambridge University Press, 2007.

[79] B. GANTER, S. O. KUZNETSOV.*Pattern Structures and Their Projections*, in "Proceedings of ICCS 2001", LNCS 2120, Springer, 2001, p. 129–142.

[80] B. GANTER, R. WILLE.*Formal Concept Analysis*, Springer, Berlin, 1999.

[81] D. HERVÉ, J.-H. RAMAROSON, A. RANDRIANARISON, F. LE BER.*Comment les paysans du corridor forestier de Fianarantsoa (Madagascar) dessinent-ils leur territoire ? Des cartes individuelles pour confronter les points de vue*, in "Cybergeo : Revue européenne de géographie / European journal of geography", 2014, 681, https://hal.archives-ouvertes.fr/hal-01057112.

[82] O. HUDRY, B. MONJARDET.*Consensus Theories. An oriented survey*, in "Mathématiques et Sciences Humaines", 2010, vol. 190, n^{o} 2, p. 139–167.

[83] M. KAYTOUE, V. CODOCEDO, A. BUZMAKOV, J. BAIXERIES, S. O. KUZNETSOV, A. NAPOLI.*Pattern Structures and Concept Lattices for Data Mining and Knowledge Processing*, in "Machine Learning and Knowledge Discovery in Databases", Porto, Portugal, A. BIFET, M. MAY, B. ZADROZNY, R. GAVALDA, D. PEDRESCHI, F. BONCHI, J. CARDOSO, M. SPILIOPOULOU (editors), Lecture Notes in Computer Science, Springer International Publishing, 2015, vol. 9286, p. 227-231 [*DOI :* 10.1007/978-3-319-23461-8_19], https://hal.archives-ouvertes.fr/hal-01188637.

[84] J.-F. MARI.*CarottAge Windows pour les données Teruti : manuel d'utilisation*, Loria & Inria Grand Est, February 2014, 43, https://hal.inria.fr/hal-00951102.

[85] J.-F. MARI, F. LE BER, E.-G. LAZRAK, M. BENOÎT, C. ENG, A. THIBESSARD, P. LEBLOND.*Using Markov Models to Mine Temporal and Spatial Data*, in "New Fundamental Technologies in Data Mining", K. FUNATSU, K. HASEGAWA (editors), Intech, 2011, p. 561–584, http://hal.inria.fr/inria-00566801/en.

[86] J.-P. METIVIER, A. LEPAILLEUR, A. BUZMAKOV, G. POEZEVARA, B. CRÉMILLEUX, S. O. KUZNETSOV, J. LE GOFF, A. NAPOLI, R. BUREAU, B. CUISSART.*Discovering structural alerts for mutagenicity using stable emerging molecular patterns*, in "Journal of Chemical Information and Modeling", 2015, vol. 55, n^{o} 5, p. 925–940 [*DOI :* 10.1021/CI500611V], https://hal.archives-ouvertes.fr/hal-01186716.

[87] P. K. NOVAK, N. LAVRAC, G. I. WEBB.*Supervised Descriptive Rule Discovery: A Unifying Survey of Contrast Set, Emerging Pattern and Subgroup Mining*, in "Journal of Machine Learning Research", 2009, vol. 10, p. 377–403, http://doi.acm.org/10.1145/1577069.1577083.

[88] G. PERSONENI, S. DAGET, C. BONNET, P. JONVEAUX, M.-D. DEVIGNES, M. SMAÏL-TABBONE, A. COULET.*Mining Linked Open Data: A Case Study with Genes Responsible for Intellectual Disability*, in "Data Integration in the Life Sciences - 10th International Conference, DILS 2014", Lisbon, Portugal, H. GALHARDAS, E. RAHM (editors), Lecture Notes in Computer Science, Springer, July 2014, vol. 8574, p. 16 - 31 [*DOI :* 10.1007/978-3-319-08590-6_2], https://hal.inria.fr/hal-01095591.

[89] N. RAMAKRISHNAN, D. KUMAR, B. MISHRA, M. POTTS, R. F. HELM.*Turning CARTwheels: An Alternating Algorithm for Mining Redescriptions*, in "Proceedings of the Tenth ACM SIGKDD International Conference on Knowledge Discovery and Data Mining", New York, NY, USA, KDD '04, ACM, 2004, p. 266–275.

[90] M. ROUANE-HACENE, M. HUCHARD, A. NAPOLI, P. VALTCHEV.*Relational Concept Analysis: Mining Concept Lattices From Multi-Relational Data*, in "Annals of Mathematics and Artificial Intelligence", January 2013, vol. 67, n^{o} 1, p. 81-108 [*DOI :* 10.1007/S10472-012-9329-3], http://hal.inria.fr/lirmm-00816300.

[91] J.-S. SERENI, J. VOLEC.*A note on acyclic vertex-colorings*, Loria & Inria Grand Est, 2013, https://hal.archives-ouvertes.fr/hal-00921122.

[92] L. SZATHMARY, P. VALTCHEV, A. NAPOLI, R. GODIN, A. BOC, V. MAKARENKOV.*A fast compound algorithm for mining generators, closed itemsets, and computing links between equivalence classes*, in "Annals of Mathematics and Artificial Intelligence", 2014, vol. 70, p. 81 - 105 [*DOI :* 10.1007/S10472-013-9372-8], https://hal.inria.fr/hal-01101140.

Project-Team PESTO

Proof techniques for security protocols

IN COLLABORATION WITH: Laboratoire lorrain de recherche en informatique et ses applications (LORIA)

IN PARTNERSHIP WITH:
CNRS

Université de Lorraine

RESEARCH CENTER
Nancy - Grand Est

THEME
Security and Confidentiality

Table of contents

Project-Team PESTO

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

Keywords:

Computer Science and Digital Science:

2.4. - Verification, reliability, certification
4.5. - Formal methods for security
4.6. - Authentication
4.8. - Privacy-enhancing technologies
7.1. - Parallel and distributed algorithms
7.4. - Logic in Computer Science

Other Research Topics and Application Domains:

6.3.2. - Network protocols
6.3.4. - Social Networks
6.6. - Embedded systems
9.8. - Privacy

1. Members

Research Scientists

Vincent Cheval [Inria, Researcher]
Véronique Cortier [Deputy team leader, CNRS, Senior Researcher, HDR]
Steve Kremer [Team Leader, Inria, Senior Researcher, HDR]
Christophe Ringeissen [Inria, Researcher, HDR]
Michaël Rusinowitch [Inria, Senior Researcher, HDR]
Mathieu Turuani [Inria, Researcher]

Faculty Members

Jannik Dreier [Univ Lorraine, Associate Professor]
Abdessamad Imine [Univ Lorraine, Associate Professor, HDR]
Laurent Vigneron [Univ Lorraine, Professor, HDR]

PhD Students

Younes Abid [Univ Lorraine, Fondation Maif, coadvised by Orpailleur]
Rémy Chrétien [ENS Cachan & LORIA, ANR Jeunes Chercheurs VIP (S. Delaune)]
Antoine Dallon [ENS Cachan & LORIA, DGA funding]
Alicia Filipiak [Cifre Orange]
Joseph Lallemand [Univ Lorraine, ERC Spooc, since September 2016]
Éric Le Morvan [Univ Lorraine, CNRS, until September 2016]
Huu Hiep Nguyen [Univ Lorraine, Cordi-S, until October 2016]
Ludovic Robin [Univ Lorraine]

Post-Doctoral Fellows

Constantin-Catalin Dragan [CNRS, FP7 ERC ProSecure]
Ivan Gazeau [Inria, ERC Spooc, since September 2016]
Peter Roenne [Inria, ANR Sequoia, until March 2016]

Visiting Scientist

Carlos Castro [UTFSM, 12 months, until June 2016]

Administrative Assistants

Emmanuelle Deschamps [Inria]
Delphine Hubert [Univ Lorraine]
Martine Kuhlmann [CNRS]

Others

Kushal Babel [2nd year student at IIT Bombay, India, from May 2016 until July 2016]
Charles Duménil [Master Mathématiques Nancy, M2, from April 2016 until September 2016]
Itsaka Rakotonirina [ENS Cachan/MPRI, M2, from May 2016 until July 2016]
Jonathan Proietto-Stallone [MIAGE Nancy, from March 2016 until August 2016]
Laura Trivino [IUT Nancy, from April 2016 until June 2016]
Clément Pascutto [ENS Paris, from June 2016 until July 2016]

2. Overall Objectives

2.1. Context

The rise of the Internet and the ubiquity of electronic devices have changed our way of life. Many face to face and paper transactions have nowadays digital counterparts: home banking, electronic commerce, e-voting, ... and even partially our social life. This digitalisation of the world comes with tremendous risks for our security and privacy as illustrated by the following examples.

Financial transactions. According to the FEVAD (French federation of remote selling and e-commerce), in France 51.1 billions Euros have been spent through e-commerce in 2013 and fraud is estimated to 1.9 billions Euros by certissim. [0] As discussed in another white paper [0] by Dave Marcus (Director of Advanced Research and Threat Intelligence, McAfee) and Ryan Sherstobitoff (Threat Researcher, Guardian Analytics) bank fraud has changed dramatically. Fraudsters are aiming to steal increasingly higher amounts from bank accounts (with single transfers over 50,000 Euros) and develop fully automated attack tools to do so. As a consequence, protocols need to implement more advanced, multi-factor authentication methods.

Electronic voting. In the last few years several European countries (Estonia, France, Norway and Switzerland) organised *legally binding political elections* that allowed (part of the) voters to cast their votes remotely via the Internet. For example, in June 2012 French people living abroad ("expats") were allowed to vote via the Internet for parliament elections. An engineer demonstrated that it was possible to write a malware that could change the value of a casted vote without any way for the voter to notice. In Estonia in the 2011 parliament election, a similar attack was reported by computer scientist Paavo Pihelgas who conducted a real life experiment with aware consenting test subjects. [0]

Privacy violations. Another security threat is the violation of an individual person's privacy. For instance the use of RFID technology can be used to trace persons, e.g. in automatic toll-paying devices [0] or in public transportation. Even though security protocols are deployed to avoid tracing by third parties, protocol design errors enabled tracing of European e-passports. [0] Recently, a flaw was identified in the 3G mobile phone protocols that allows a third party, i.e., not only the operator, to trace telephones [33]. Also, anonymised data of social networks has been effectively used to identify persons by comparing data from several social networks. [0]

[0] Livre Blanc: La fraude dans le e-commerce, certissim.
[0] Dissecting Operation High Roller. http://www.mcafee.com/uk/resources/reports/rp-operation-high-roller.pdf
[0] The Supreme Court dismissed an electoral complaint regarding e-voting security. http://www.nc.ee/?id=1235
[0] A Pass on Privacy? The New York Times, July 17, 2005. http://www.nytimes.com/2005/07/17/magazine/17WWLN.html
[0] Defects in e-passports allow real-time tracking. The Register, 26th January 2010. http://www.theregister.co.uk/2010/01/26/epassport_rfid_weakness/
[0] Social sites dent privacy efforts. BBC, March 27 2009. http://news.bbc.co.uk/2/hi/technology/7967648.stm

2.2. Objectives

The aim of the Pesto project is to build formal models and techniques, for computer-aided analysis and design of security protocols (in a broad sense). While historically the main goals of protocols were confidentiality and authentication the situation has changed. E-voting protocols need to guarantee privacy of votes, while ensuring transparency of the election; electronic devices communicate data by the means of web services; RFID and mobile phone protocols have to guarantee that people cannot be traced. Due to malware, security protocols need to rely on additional mechanisms, such as trusted hardware components or multi-factor authentication, to guarantee security even if the computing platform is a priori untrusted. Current existing techniques and tools are however unable to analyse the properties required by these new protocols and take into account the newly deployed mechanisms and associated attacker models.

3. Research Program

3.1. Modelling

Before being able to analyse and properly design security protocols, it is essential to have a model with a precise semantics of the protocols themselves, the attacker and its capabilities, as well as the properties a protocol needs to ensure.

Most current languages for protocol specification are quite basic and do not provide support for global state, loops, or complex data structures such as lists, or Merkle trees. As an example we may cite Hardware Security Modules that rely on a notion of *mutable global state* which does not arise in traditional protocols, see e.g. the discussion by Herzog [46].

Similarly, the properties a protocol should satisfy are generally not precisely defined, and stating the "right" definitions is often a challenging task in itself. In the case of authentication, many protocol attacks were due to the lack of a precise meaning, cf [44]. While the case of authentication has been widely studied, the recent digitalisation of all kinds of transactions and services, introduces a plethora of new properties, including for instance anonymity in e-voting, untraceability of RFID tokens, verifiability of computations that are out-sourced, as well as sanitisation of data in social networks. We expect that many privacy anonymity properties may be modelled as particular observational equivalences in process calculi [40], or indistinguishability between cryptographic games [2], sanitisation of data may also rely on information-theoretic measures.

We also need to take into account that the attacker model changes. While historically the attacker was considered to control the communication network, we may nowadays argue that even (part of) the host executing the software may be compromised through, e.g., malware. This situation motivates the use of secure elements and multi-factor authentication with out-of-band channels. A typical example occurs in e-commerce: to validate an online payment a user needs to enter an additional code sent by the bank via sms to the user's mobile phone. Such protocols require the possession of a physical device in addition to the knowledge of a password which could have been leaked on an untrusted platform. The fact that data needs to be copied by a human requires these data to be *short*, and hence amenable to brute-force attacks by an attacker or guessing.

3.2. Analysis

3.2.1. Generic proof techniques

Most automated tools for verifying security properties rely on techniques stemming from automated deduction. Often existing techniques do however not apply directly, or do not scale up due to the state explosion problems. For instance, the use of Horn clause resolution techniques requires dedicated resolution methods [34][3]. Another example is unification modulo equational theory, which is a key technique in several tools, e.g. [43]. Security protocols, however require to consider particular equational theories that are not naturally studied in classical automated reasoning. Sometimes, even new concepts have been introduced. One example is the finite variant property [38], which is used in several tools, e.g., *Akiss* [3], Maude-NPA [43] and Tamarin [47].

Another example is the notion of asymmetric unification [42] which is a variant of unification used in Maude-NPA to perform important *syntactic* pruning techniques of the search space, even when reasoning modulo an equational theory. For each of these topics we need to design efficient decision procedures for a variety of equational theories.

3.2.2. Dedicated procedures and tools

We will also design dedicated techniques for automated protocol verification. While existing techniques for security protocol verification are efficient and have reached maturity for verification of confidentiality and authentication properties (or more generally safety properties), our goal is to go beyond these properties and the standard attacker models, verifying the properties and attacker models identified in Section 3.1. This includes techniques that

- can analyse *indistinguishability* properties, including for instance anonymity and unlinkability properties, but also properties stated in simulation-based (also known as universally composable) frameworks, which express the security of a protocol as an ideal (correct by design) system;
- take into account protocols that rely on *mutable global state* which does not arise in traditional protocols, but is essential when verifying tamper-resistant hardware devices, e.g., the RSA PKCS#11 standard, IBM's CCA and the trusted platform module (TPM);
- consider attacker models for protocols relying on *weak secrets* that need to be copied or remembered by a human, such as multi-factor authentication.

These goals are beyond the scope of most current analysis tools and require both theoretical advances in the area of verification, as well as the design of new efficient verification tools.

3.3. Design

Given our experience in formal analysis of security protocols, including both protocol proofs and findings of flaws, it is tempting to use our experience to design protocols with security in mind and security proofs. This part includes both provably secure design techniques, as well as the development of new protocols.

3.3.1. General design techniques

Design techniques will include *composition results* that allow one to design protocols in a modular way [39], [36]. Composition results come in many flavours: they may allow one to compose protocols with different objectives, e.g. compose a key exchange protocol with a protocol that requires a shared key or rely on a protocol for secure channel establishment, compose different protocols in parallel that may re-use some key material, or compose different sessions of a same protocol.

Another area where composition is of particular importance is Service Oriented Computing, where an "orchestrator" must combine some available component services, while guaranteeing some security properties. In this context, we will work on the automated synthesis of the orchestrator or monitors for enforcing the security goals. These problems require to study new classes of automata that communicate with structured messages.

3.3.2. New protocol design

We will also design new protocols. Application areas that seem of particular importance are:

- External hardware devices such as security APIs that allow one for flexible key management, including key revocation, and their integration in security protocols. The security *fiasco* of the PKCS#11 standard [35], [41] witnesses the need for new protocols in this area.
- Election systems that provide strong security guarantees. We already work (in collaboration with the Caramba team) on a prototype implementation of an e-voting system, Belenios (http://belenios.gforge.inria.fr).
- Mechanisms for publishing personal information (e.g. on social networks) in a controlled way.

4. Application Domains

4.1. Formal methods for Cryptographic protocols

Security protocols, such as TLS, Kerberos or ssh, are the main tool for securing our communications. The aim of our work is to propose models that are expressive enough to formally represent protocol executions in the presence of an adversary, formal definitions of the security properties to be satisfied by these protocols, and design automated tools able to analyse them and possibly exhibit design flaws.

4.2. Automated reasoning

Many techniques for symbolic verification of security are rooted in automated reasoning. A typical example is equational reasoning used to model the algebraic properties of a cryptographic primitive. Our work therefore aims to improve and adapt existing techniques or propose new ones when needed for reasoning about security.

4.3. Electronic voting

Electronic elections have in the last years been used in several countries for politically binding elections. The use in professional elections is even more widespread. The aim of our work is to increase our understanding of the security properties needed for secure elections, propose techniques for analysing e-voting protocols, design of state-of-the-art voting protocols, but also to highlight the limitations of e-voting solutions.

4.4. Privacy in social networks

Treatment of information released by users on social networks can violate a user's privacy. The goal of our work is to allow one a controlled information release while guaranteeing a user's privacy.

5. Highlights of the Year

5.1. Highlights of the Year

Steve Kremer gave a keynote talk at the 29th IEEE Computer Security Foundations Symposium (CSF'16).

5.1.1. Awards

Véronique Cortier, Antoine Dallon and Stéphanie Delaune received the EASST best paper award of the ETAPS conference for the paper [24].
BEST PAPERS AWARDS :
[24] **5th International Conference on Principles of Security and Trust (POST'16)**. V. CORTIER, A. DALLON, S. DELAUNE.

6. New Software and Platforms

6.1. Akiss

Akiss (Active Knowledge in Security Protocols) is a tool for verifying indistinguishability properties in cryptographic protocols, modelled as trace equivalence in a process calculus. Indistinguishability is used to model a variety of properties including anonymity properties, strong versions of confidentiality and resistance against offline guessing attacks, etc. *Akiss* implements a procedure to verify equivalence properties for a bounded number of sessions based on a fully abstract modelling of the traces of a bounded number of sessions of the protocols into first-order Horn clauses and a dedicated resolution procedure. The procedure can handle a large set of cryptographic primitives, namely those that can be modeled by an optimally reducing convergent rewrite system. The tool also includes the possibility for checking everlasting indistinguishability properties [32].

The tool is still under active development, including optimisations to improve efficiency, but also the addition of new features, such as the possibility to model protocols using weak secrets, and the addition of support for exclusive or.

The *Akiss* tool is freely available at https://github.com/akiss/akiss.

6.2. ATSE

We develop *CL-AtSe*, a Constraint Logic based Attack Searcher for cryptographic protocols, initiated and continued by the European projects *AVISPA*, AVANTSSAR (for web-services) and Nessos respectively. The *CL-AtSe* approach to verification consists in a symbolic state exploration of the protocol execution for a bounded number of sessions, thus is both correct and complete. *CL-AtSe* includes a proper handling of sets, lists, choice points, specification of any attack states through a language for expressing e.g., secrecy, authentication, fairness, or non-abuse freeness, advanced protocol simplifications and optimizations to reduce the problem complexity, and protocol analysis modulo the algebraic properties of cryptographic operators such as XOR (exclusive or) and Exp (modular exponentiation).

CL-AtSe has been successfully used to analyse protocols from e.g., France Telecom R&D, Siemens AG, IETF, Gemalto, Electrum in funded projects. It is also employed by external users, e.g., from the AVISPA's community. Moreover, *CL-AtSe* achieves good analysis times, comparable and sometimes better than other state-of-the art tools.

CL-AtSe has been enhanced in various ways. It fully supports the Aslan semantics designed in the context of the AVANTSSAR project, including Horn clauses (for intruder-independent deductions, e.g., for credential management), and a large fragment of LTL-based security properties. A Bugzilla server collects bug reports, and online analysis and orchestration are available on our team server (https://cassis.loria.fr). Large models can be analysed on the TALC Cluster in Nancy with parallel processing. *CL-AtSe* also supports negative constraints on the intruder's knowledge, which reduces drastically the orchestrator's processing times and allows separation of duties and non-disclosure policies, as well as conditional security properties, like: i) an authentication to be verified iff some session key is safe; ii) relying on a leaking condition on some private data instead of an honesty predicate to trigger or block some agent's property. This was crucial for e.g., the Electrum's wallet where all clients can be dishonest but security guarantees must be preserved anyway.

6.3. Belenios

In collaboration with the Caramba project-team, we develop an open-source private and verifiable electronic voting protocol, named *Belenios*. Our system is an evolution and a new implementation of an existing system, Helios, developed by Ben Adida, and used e.g., by UCL and the IACR association in real elections. The main differences with Helios are a cryptographic protection against ballot stuffing and a practical threshold decryption system that allows us to split the decryption key among several authorities, k out of n authorities being sufficient to decrypt. We will continue to add new cryptographic and protocol improvements to offer a secure, proved, and practical electronic voting system.

Belenios has been implemented (cf. http://belenios.gforge.inria.fr) by Stéphane Glondu (SED Team). Since 2015, it is used by CNRS for remote election among its councils and since 2016, it used by Inria to elect representatives in the "comités de centre" of each Inria center. It has also been used to elect the leader of the GdR-IM working groups C2 and Calcul Formel. It has also been used in smaller elections (e.g., to choose an invited speaker).

6.4. Tamarin

The *TAMARIN* prover is a security protocol verification tool that supports both falsification and unbounded verification of security protocols specified as multiset rewriting systems with respect to (temporal) first-order properties and a message theory that models Diffie-Hellman exponentiation combined with a user-defined subterm-convergent rewriting theory.

Its main advantages are its ability to handle stateful protocols and its interactive proof mode. Moreover, it has recently been extended to verify equivalence properties.

The tool is developed jointly by the PESTO team, the Institute of Information Security at ETH Zurich, and the University of Oxford.

TAMARIN is freely available at http://tamarin-prover.github.io/. In a joint effort, the partners wrote and published a user manual in 2016, available from the same website.

6.5. Sapic

SAPIC is a tool that translates protocols from a high-level protocol description language akin to the applied pi-calculus into multiset rewrite rules, that can then be be analysed using the *TAMARIN* prover. *TAMARIN* has also bee extended with dedicated heuristics that exploit the form of translated rules and favour termination.

SAPIC offers support for the analysis of protocols that include states, for example Hardware Security Tokens communicating with a possibly malicious user, or protocols that rely on databases. It also allows us to verify liveness properties and a recent extension adds a notion of location and reporting used for modelling trusted execution environments. It has been successfully applied on several case studies including the Yubikey authentication protocol, extensions of the PKCS#11 standard and fair exchange protocols.

SAPIC is freely available at http://sapic.gforge.inria.fr/.

7. New Results

7.1. Modelling

7.1.1. New protocol and adversary models

Participants: Jannik Dreier, Steve Kremer.

Isolated Execution Environments (IEEs), such as ARM TrustZone and Intel SGX, offer the possibility to execute sensitive code in isolation from other malicious programs, running on the same machine, or a potentially corrupted OS. A key feature of IEEs is the ability to produce reports binding cryptographically a message to the program that produced it, typically ensuring that this message is the result of the given program running on an IEE. In collaboration with Jacomme (ENS Cachan) and Scerri (Univ. Bristol), Kremer presented a symbolic model for specifying and verifying applications that make use of such features. For this they introduced the SℓAPiC process calculus to reason about reports issued at given locations. They also provide tool support, extending the SAPIC/TAMARIN toolchain and demonstrate the applicability of their framework on several examples implementing secure outsourced computation (SOC), a secure licensing protocol and a one-time password protocol that all rely on such IEEs. This work has been accepted for publication at EuroS&P'17 [27].

Most security properties are modelled as *safety* properties (*"bad things do not happen"*). Another important class of properties is that of *liveness* properties (*"eventually, good things happen"*). Reasoning about the class of *liveness* properties of cryptographic protocols, has received little attention in the literature, even though this class is vital in many security-sensitive applications, such as fair exchange protocols, or security layers in industrial control systems. In collaboration with Backes and Künnemann (U. Saarland, Germany), Dreier and Kremer have designed a protocol and adversary model that are suitable for reasoning about liveness properties. Tool support is also provided by extending the *SAPIC/TAMARIN* tool chain and several case studies demonstrate the effectiveness of the approach. This work has been accepted for publication at EuroS&P'17 [20].

7.1.2. New properties

Participants: Véronique Cortier, Jannik Dreier.

Defining security properties correctly is often a challenging problem on its own: too strict definitions may lack generality and exclude systems that should be considered as secure, while relaxing definitions may lead to accepting insecure systems.

In e-voting, *verifiability* is the property meant to defend against voting devices and servers that have programming errors or are outright malicious. While the first formal definitions of verifiability were devised in the late 1980s already, new verifiability definitions are still being proposed. The definitions differ in various aspects, including the classes of protocols they capture and even their formulations of the very core of the meaning of verifiability. This is an unsatisfying state of affairs, leaving the research on the verifiability of e-voting protocols and systems in a fuzzy state. Cortier, in collaboration with Galindo (U. Birmingham, UK), Küsters, Müller (U. Trier, Germany) and Truderung (Polyas GmbH, Germany), review all formal definitions of verifiability proposed in the literature and cast them in a framework proposed by the KTV framework, yielding a uniform treatment of verifiability. This enables a detailed comparison of the various definitions of verifiability from the literature and a discussion of advantages and disadvantages, limitations and problems. Finally, a general definition of verifiability is distilled, which can be instantiated in various ways. This work has been presented at S&P'16 [26].

Industrial systems are nowadays regularly the target of cyberattacks, the most famous being Stuxnet. At the same time such systems are increasingly interconnected with other systems and insecure media such as Internet. In contrast to other IT systems, industrial systems often do not only require classical properties like data confidentiality or authentication of the communication, but have special needs due to their interaction with the physical world. For example, the reordering or deletion of some commands sent to a machine can cause the system to enter an unsafe state with potentially catastrophic effects. To prevent such attacks, the integrity of the message flow is necessary.

In joint work with Lafourcade (Université Clermont-Ferrand), Potet, and Puys (University Grenoble Alpes), Dreier developed a formal definition of Flow Integrity in the context of industrial systems. The framework is applied to two well-known industrial protocols: OPC-UA and MODBUS. Using *TAMARIN*, a cryptographic protocol verification tool, they identified several design flaws in some of the different versions of these protocols. We also discussed how to efficiently model counters and timestamps in *TAMARIN*, as they are key ingredients of the analyzed protocols. This work is currently under submission.

7.2. Analysis

7.2.1. Analysis of equivalence properties

Participants: Vincent Cheval, Véronique Cortier, Antoine Dallon, Ivan Gazeau, Steve Kremer, Christophe Ringeissen.

Automatic tools based on symbolic models have been successful in analyzing security protocols. These tools are particularly well adapted for trace properties (e.g. secrecy or authentication). However, they often fail to analyse equivalence properties. Equivalence properties can express a variety of security properties, including in particular privacy properties (vote privacy, anonymity, untraceability). Several decision procedures have already been proposed but the resulting tools are often rather limited, and lack efficiency.

In the case of a passive adversary, Ringeissen, in collaboration with Marshall (U. of Mary Washington, USA) and Erbatur (LMU, Germany) present new combination techniques for the study of deducibility and static equivalence in unions of equational theories sharing constructors. This allows us to develop new modularity results for the decidability of deducibility and static equivalence. In turn, this should allow for the security analysis of protocols which previous disjoint combination methods could not address because their axiomatization corresponds to the union of non-disjoint equational theories.

In case of an active adversary, and a bounded number of sessions, we made several advances. In [14], Cheval and Kremer, in collaboration with Chadha (U. of Missouri, USA) and Ciobâcă (U. Iasi, Romania), present the theory underlying the *Akiss* tool, a Horn clause resolution based procedure for both under- and over-approximating trace equivalence. They show partial correctness for a large class of cryptographic primitives, modelled as an arbitrary convergent equational theory that has the finite variant properties. Additionally, termination is shown for subterm convergent theories. Gazeau and Kremer, in collaboration with Baelde (LSV, ENS Cachan) and Delaune (IRISA) have extended the *Akiss* tool with support for exclusive or. They analyse unlinkability in several RFID protocols and resistance to guessing attacks of several password base protocols. Cortier and Dallon, in collaboration with Delaune (IRISA) propose a novel algorithm, based on graph planning and SAT-solving, which significantly improves the efficiency of the analysis of equivalence properties. The resulting implementation, SAT-Equiv, can analyze several sessions where most tools have to stop after one or two sessions. Finally, Cheval and Kremer propose a novel decision procedure for verifying trace equivalence. Unlike most existing tools, they support a rich class of cryptographic primitives and protocols that may use else branches. An implementation of the procedure is currently under development.

These results are currently under submission.

7.2.2. Simplification results

Participants: Véronique Cortier, Antoine Dallon, Steve Kremer.

Bounding the number of agent identies is a current practice when modeling a protocol. In 2003, it has been shown that one honest agent and one dishonest agent are indeed sufficient to find all possible attacks, for trace properties. This is no longer the case for equivalence properties, crucial to express many properties such as vote privacy or untraceability. As a first result of his PhD, Antoine Dallon has shown that it is sufficient to consider two honest agents and two dishonest agents for equivalence properties, for deterministic processes with standard primitives and without else branches. More generally, we show how to bound the number of agents for arbitrary constructor theories and for protocols with simple else branches. We show that our hypotheses are tight, providing counter-examples for non action-deterministic processes, non constructor theories, or protocols with complex else branches. This work has been presented at POST 2016 [24] and obtained the EASST best paper award of the ETAPS conference.

When verifying e-voting protocols, one of the difficulties is that they need to be secure for an arbitrary number of malicious voters. In collaboration with Arapinis (U. Edinburgh, UK), Cortier and Kremer identify a class of voting protocols for which only a small number of voters needs to be considered: if there is an attack on vote privacy, for an arbitrary number of honest and dishonest voters, then there is also an attack that involves at most 3 voters (2 honest voters and 1 dishonest voter). In the case where the protocol allows a voter to cast several votes and counts, e.g., only the last one, we also reduce the number of ballots required for an attack to 10, and under some additional hypotheses, 7 ballots. They illustrate the applicability of our results on several case studies, including different versions of Helios and Prêt-à-Voter, as well as the JCJ protocol. For some of these protocols the ProVerif tool is used to provide the first formal proofs of privacy for an unbounded number of voters. This work has been presented at ESORICS 2016 [19].

7.2.3. Analysis of stateful security protocols

Participants: Jannik Dreier, Charles Duménil, Steve Kremer.

In collaboration with Künnemann (U. Saarland, Germany), Kremer proposes *SAPIC* (stateful applied pi calculus), a process calculus with constructs for manipulation of a global state by processes running in parallel. They show that this language can be translated to multiset rewriting rules whilst preserving all security properties expressible in a dedicated first-order logic for security properties. The translation has been implemented in a prototype tool which uses the *TAMARIN* prover as a backend. The tool is applied to several case studies among which a simplified fragment of PKCS#11, the Yubikey security token, and an optimistic contract signing protocol. This work has been published in the Journal of Computer Security [15]. Dreier, Duménil and Kremer, in collaboration with Sasse (ETH Zurich, Switzerland) improve the underlying theory and the *TAMARIN* tool to allow for more general user-specified equational theories: the extension supports arbitrary convergent equational theories that have the finite variant property, making *TAMARIN* the first tool to support at the same time this large set of user-defined equational theories, protocols with global mutable state, an unbounded number of sessions, and complex security properties. The effectiveness of this generalization is demonstrated by analyzing several protocols that rely on blind signatures, trapdoor commitment schemes, and ciphertext prefixes that were previously out of scope. This work has been accepted for publication at POST'17.

7.2.4. *Analysis of e-voting protocols*

Participants: Véronique Cortier, Constantin-Catalin Dragan.

Cortier and Dragan provide the first machine-checked proof of privacy-related properties (including ballot privacy) for an electronic voting protocol in the computational model. They target the popular Helios family of voting protocols, for which they identify appropriate levels of abstractions to allow the simplification and convenient reuse of proof steps across many variations of the voting scheme. The resulting framework enables machine-checked security proofs for several hundred variants of Helios and should serve as a stepping stone for the analysis of further variations of the scheme.

In addition, they highlight some of the lessons learned regarding the gap between pen-and-paper and machine-checked proofs, and report on the experience with formalizing the security of protocols at this scale. This work is submitted for publication.

7.2.5. *Analysis of Electrum Bitcoin wallet*

Participants: Michaël Rusinowitch, Mathieu Turuani.

Electrum is a popular Bitcoin wallet. We introduce a formal modeling in ASLan++ of the two-factor authentication protocol used by the Electrum Bitcoin wallet. This allows us to perform an automatic analysis of the wallet and show that it is secure for standard scenarios in the Dolev Yao model [30]. The result could be derived thanks to some advanced features of the Cl-Atse protocol analyzer such as the possibility to specify i) new intruder deduction rules with clauses and ii) non-deducibility constraints.

7.2.6. *Satisfiability Modulo Bridging Theories*

Participant: Christophe Ringeissen.

Bridging theories are equational theories defining recursive functions. They are useful to handle equational theories of interest in protocol analysis, as advocated in [48], where a locality approach is promoted to solve the satisfiability problem. In collaboration with Pascal Fontaine (Veridis project-team) and Paula Chocron (IIIA-CSIC Barcelona), we investigate a combination approach for the satisfiability problem modulo this particular non-disjoint union of theories, where a source theory is connected to a target one through a bridging function. In 2016, we have prepared a new full paper unifying previous results presented respectively at CADE 2015 [4] and FroCoS 2015. In that papers, we focused on source theories admitting term-generated models. In [21], we have also explored an extension to deal with terms modulo a congruence relation. This joint work with Raphaël Berthon (ENS Rennes) allows us to consider not only trees but also data structure theories such as lists, multisets and sets.

7.2.7. *Analysis of Security Properties for an Unbounded Number of Sessions*

Participants: Jonathan Proietto-Stallone, Mathieu Turuani, Laurent Vigneron.

The internship of Jonathan Proietto-Stallone has permitted to study the method described in [37] for analyzing protocols without bounding the number of sessions. We have clarified the formalization of this method, including the consideration of xor and exp operators, and implemented it in *CL-AtSe*.

7.3. Design

7.3.1. E-voting protocols

Participants: Véronique Cortier, Steve Kremer, Peter Roenne.

We propose a new voting scheme, BeleniosRF, that offers both receipt-freeness and end-to-end verifiability. It is receipt-free in a strong sense, meaning that even dishonest voters cannot prove how they voted. We provide a game-based definition of receipt-freeness for voting protocols with non-interactive ballot casting, which we name strong receipt-freeness (sRF). To our knowledge, sRF is the first game-based definition of receipt-freeness in the literature, and it has the merit of being particularly concise and simple. Built upon the Helios protocol, BeleniosRF inherits its simplicity and does not require any anti-coercion strategy from the voters. We implement BeleniosRF and show its feasibility on a number of platforms, including desktop computers and smartphones. This work has been presented at CCS 2016 [26].

Another challenging problem in e-voting is to provide guarantees when the voting platform itself is corrupted. Du-Vote [45] is a recently presented remote electronic voting scheme that aims to be malware tolerant, i.e., provide security even in the case where the platform used for voting has been compromised by dedicated malware. For this it uses an additional hardware token, similar to tokens distributed in the context of online banking. Du-Vote aims at providing vote privacy as long as either the vote platform or the vote server is honest. For verifiability, the security guarantees are even higher, as even if the token's software has been changed, and the platform and the server are colluding, attempts to change the election outcome should be detected with high probability. We provide an extensive security analysis of Du-Vote and show several attacks on both privacy as well as verifiability. We also propose changes to the system that would avoid many of these attacks. This work has been presented at Euro S&P 2016 [28].

7.3.2. Designing and proving an EMV-compliant payment protocol for mobile devices

Participants: Véronique Cortier, Alicia Filipiak.

In collaboration with Gharout, Traoré and Florent (Orange Labs), we devised a payment protocol that can be securely used on mobile devices, even infected by malicious applications. Our protocol only requires a light use of Secure Elements, which significantly simplifies certification procedures and protocol maintenance. It is also fully compatible with the EMV-SDA protocol and allows off-line payments for the users. We provide a formal model and full security proofs of the protocol using the TAMARIN prover. This work has been accepted for publication at Euro S&P'17 [25].

7.3.3. Composition and design of PKIs

Participants: Vincent Cheval, Véronique Cortier.

Public Key Infrastructures (PKIs) is the backbone of public key cryptography, as it ensures that public keys can be correctly linked to identities. Their security typically relies on honest Certificate Authorities that distribute and/or generate keys to all parties. This trust assumption is a vulnerability exploited in numerous attacks. Recent proposals using public logs have succeeded in making certificate management more transparent and verifiable. However, those proposals involve a fixed set of authorities which means an oligopoly is created. Another problem with current log-based system is their heavy reliance on trusted parties that monitor the logs. Cheval, in collaboration with Ryan and Yu (U. Birmingham, UK) propose a distributed transparent key infrastructure (DTKI), which greatly reduces the oligopoly of service providers and allows verification of the behaviour of trusted parties. Their work also formalises the public log data structure and provides a formal analysis of the security that DTKI guarantees. The work has been published in The Computer Journal [17].

In protocol analysis one makes the (strong) assumption that honestly generated keys are available to all parties and that the link between identities and public keys is fixed and known to everyone. The abstraction is grounded in solid intuition but there are currently no theoretical underpinnings to justify its use. Cheval and Cortier, in collaboration with Warinschi (U. Bristol, UK), initiate a rigorous study of how to use PKIs within other protocols, securely. They first show that the abstraction outlined above is in general unsound by exhibiting a simple protocol which is secure with idealized key distribution but fails in the presence of more realistic

PKI instantiation. Their main result is a generic composition theorem that identifies under which conditions protocols that require public keys can safely use any PKI protocol (which satisfies a security notion which we identify). Interestingly, unlike most existing composition results in symbolic models they do not require full tagging of the composed protocols. Furthermore, the results confirm the recommended practice that keys used in the PKI should not be used for any other cryptographic task. This work is currently under submission.

7.3.4. Physical Zero-Knowledge Proofs

Participant: Jannik Dreier.

In this work we develop physical algorithms to realize zero-knowledge proofs for Akari, Takuzu, Kakuro, and KenKen, which are logic games similar to Sudoku. The zero-knowledge proofs allow a player to show that he knows a solution without revealing it. These interactive proofs can be realized with simple office material as they only rely on cards and envelopes. They can thus be used for example for scientific outreach activities, or in teaching. Moreover, we also formalized our algorithms and proved their security. This joint work with Bultel (U. Clermont-Ferrand), Dumas (U. Grenoble Alpes), and Lafourcade (U. Clermont-Ferrand) was published at FUN 2016 [22].

7.3.5. Privacy Protection in Social Networks

Participants: Younes Abid, Abdessamad Imine, Huu Hiep Nguyen, Clément Pascutto, Michaël Rusinowitch, Laura Trivino.

Hiep Nguyen's PhD thesis addresses three privacy problems of social networks: graph anonymization, private community detection and private link exchange. The main goal is to provide new paradigms for publication of social graphs in noisy forms, private community detection over graphs as well as distributed aggregation of graphs via noisy link exchange processes. The graph anonymization problem is solved via two different semantics: uncertainty semantics and differential privacy. For uncertainty semantics, a general obfuscation model is proposed that keeps the expected node degree equal to those in the unanonymized graph. Over the last decade, a great number of algorithms for community detection have been proposed to deal with the increasingly complex networks. However, the problem of doing this in a private manner is rarely considered. We analyze the major challenges behind the problem and propose several schemes to tackle them under differential privacy from two perspectives: input perturbation and algorithm perturbation [29].

We address the problem of rapidly disclosing many friendship links using only legitimate queries (i.e., queries and tools provided by the targeted social network). Our study [18] sheds new light on the intrinsic relation between communities (usually represented as groups) and friendships between individuals. To develop an efficient attack we analysed group distributions, densities and visibility parameters from a large sample of a social network. By effectively exploring the target group network, our proposed algorithm is able to perform friendship and mutual-friend attacks along a strategy that minimizes the number of queries. Pascutto has established a state-of-the-art on inference techniques for social networks. Trivino has developed a user interface for privacy risk evaluation on social networks.

8. Bilateral Contracts and Grants with Industry

8.1. Electronic Voting Systems

Participants: Véronique Cortier, Mathieu Turuani.

Since 2014, a collaboration agreement has been signed between Loria and Scytl, a Spanish company who is proposing solutions for the organization of on-line elections, including legally binding elections, in several countries. In this context, Scytl has signed a contract with the Pesto team as well as the University of Birmingham (David Galindo) to design a formal proof of both verifiability and privacy of the protocol developed by Scytl, for a deployment in Switzerland.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. CNRS

- CNRS PEPS JCJC INS2I 2016 project VESPA *Verifying Equivalence Security in Protocols: Tools and Algorithms*, duration: 1 year, leader: Jannik Dreier, participant: Vincent Cheval.

  Privacy-related notions such as unlinkability and anonymity are usually expressed as equivalence properties, which are notoriously difficult to prove. Due to the complexity of the protocols and the properties, tool support is a must, yet currently rather limited. Notably, there is currently no tool that can verify unlinkability of the electronic passport for an unbounded number of sessions, or anonymity in certain classic electronic cash protocols. The goal of this project is to enable the proofs for these and similar protocols using two complementary approaches: (1) by significantly advancing the state of the art of the algorithms used inside the tools to improve handling of branching and cryptographic primitives, and (2) by providing new reduction results that simplify the tools' inputs.
- CNRS PEPS INS2I 2016 project ASSI *Analyse de Sécurité de Systèmes Industriels*, duration: 1 year, leader: Pascal Lafourcade (Université Clermont-Ferrand), participant PESTO: Jannik Dreier, other participants: Marie-Laure Potet, Maxime Puys (University Grenoble-Alpes).

  The goal of the project is to develop an approach to verify protocols used in industrial control (SCADA) systems using tools such as *TAMARIN* or ProVerif. These protocols have specific security requirements such as flow integrity, going beyond the classical authentication and secrecy properties. The project also aims at analyzing different intruder models matching the particularities of industrial systems, and to develop specific modeling and verification techniques.

9.1.2. ANR

- ANR SEQUOIA *Security properties, process equivalences and automated verification*, duration: 4 years, since October 2014, leader: Steve Kremer. Most protocol analysis tools are restricted to analyzing reachability properties while many security properties need to be expressed in terms of some process equivalence. The increasing use of observational equivalence as a modeling tool shows the need for new tools and techniques that are able to analyze such equivalence properties. The aims of this project are *(i)* to investigate which process equivalences – among the plethora of existing ones – are appropriate for a given security property, system assumptions and attacker capabilities; *(ii)* to advance the state-of-the-art of automated verification for process equivalences, allowing for instance support for more cryptographic primitives, relevant for case studies; *(iii)* to study protocols that use low-entropy secrets expressed using process equivalences; *(iv)* to apply these results to case studies from electronic voting.

9.1.3. Fondation MAIF

Project *Protection de l'information personnelle sur les réseaux sociaux*, duration: 3 years, started in October 2014. The goal of the project is to lay the foundation for a risk verification environment on privacy in social networks. Given social relations, this environment will rely on the study of metrics to characterize the security level for a user. Next, by combining symbolic and statistical techniques, an objective is to synthesize a model of risk behavior as a rule base. Finally, a verifier à la model-checking will be developed to assess the security level of user. Partners are Pesto (leader), Orpailleur and Fondation Maif.

9.2. European Initiatives

9.2.1. FP7 & H2020 Projects

- ProSecure (2011-2016) [0]— ERC Starting Grant Project on Provably secure systems: foundations, design, and modularity. The long-term aim of the project is to develop provably secure systems such as security protocols. The goal is to propose foundations for a careful analysis and design of large classes of up-to-date protocols. To achieve this goal, the project is structured in three main tasks. First, we develop general verification techniques for new classes of protocols that are of primary interest in nowadays life like e-voting protocols, routing protocols or security APIs. Second, we consider the cryptographic part of the primitives that are used in such protocols (encryption, signatures, ...), obtaining higher security guarantees. Third, we propose modular results both for the analysis and design of protocols. Véronique Cortier is the leader of the project.
- SPOOC (2015–2020) [0]— ERC Consolidator Grant on Automated Security Proofs of Cryptographic Protocols: Privacy, Untrusted Platforms and Applications to E-voting Protocols.

  The goals of the Spooc project are to develop solid foundations and practical tools to analyze and formally prove security properties that ensure the privacy of users as well as techniques for executing protocols on untrusted platforms. We will

  – develop foundations and practical tools for specifying and formally verifying new security properties, in particular privacy properties;

  – develop techniques for the design and automated analysis of protocols that have to be executed on untrusted platforms;

  – apply these methods in particular to novel e-voting protocols, which aim at guaranteeing strong security guarantees without need to trust the voter client software.

  Steve Kremer is the leader of the project.

9.3. International Initiatives

9.3.1. Inria International Partners

- Collaboration with David Basin, Ralf Sasse and Lara Schmid (ETH Zurich), Cas Cremers (University of Oxford), and Sasa Radomirovic (University of Dundee) on the improvement of the *TAMARIN* prover and the elaboration of a user manual.
- Collaboration with Bogdan Warinschi (Bristol University) on defining game-based privacy for e-voting protocols and isolated execution environments.
- Collaboration with Myrto Arapinis (University of Edinburgh) on simplification results for the formal analysis of e-voting protocols.
- Collaboration with Matteo Maffei (CISPA, Germany) on type systems for e-voting systems.
- Collaboration with Michael Backes and Robert Künnemann (CISPA, Germany) on automated verification of security protocols.
- Collaboration with Paliath Narendran's group (SUNY Albany) on automated deduction.
- Collaboration with Hanifa Boucheneb's group (Ecole Polytechnique de Montréal) on model-checking of collaborative systems.
- Collaboration with John Mullins's group (Ecole Polytechnique de Montréal) on information hiding.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

- Carlos Castro (UTSM Valparaíso, Chile), July 2015 - June 2016, partly funded as Inria invited researcher

[0] http://prosecure.loria.fr
[0] https://members.loria.fr/SKremer/files/spooc/index.html

- David Galindo (University of Bimingham), April 2016
- Bogdan Warinschi (University of Bristol), November 2016

10. Dissemination

10.1. Promoting Scientific Activities

The CNIL (Commission Nationale Informatique et Liberté) has official recommendations in terms of electronic voting.[0] These recommendations influence the design of e-voting systems that are deployed in France. However, some of the recommendations seem a bit outdated and dedicated to particular classes of systems. Even more importantly, the CNIL recommendations focus on vote privacy but do not say much about verifiability. Véronique Cortier, David Galindo, and Stéphane Glondu formulated new recommendations, submitted to the CNIL. They met some CNIL members to discuss how to integrate some of the propositions to the new version of the CNIL recommendations that should appear in 2017.

Moreover, Véronique Cortier was auditioned by the AFE (Assemblée des Francais de l'étranger) on the security of electronic voting. She has also presented the Belenios protocol to the MENESR (Ministère de l'Éducation National, de l'Enseignement Supérieur et de la Recherche) and to the Open Government Summit at the Sénat. Steve Kremer gave a talk on e-voting at the "Colloque Sécurité Informatique : mythes et réalité" organised by CNRS.

10.1.1. Scientific Events Selection

10.1.1.1. General Chair, Scientific Chair

- Véronique Cortier: HotSpot 2016, 4th Workshop on Hot Issues in Security Principles and Trust. Affiliated with ETAPS 2016.
- Steve Kremer: GRSRD 2016, Grande Region Security and Reliability Day, Nancy, March 2016 (co-chair with J. Pang, U. Luxembourg).

10.1.1.2. Program Committee Chair

- Véronique Cortier: HotSpot 2016, 4th Workshop on Hot Issues in Security Principles and Trust. Affiliated with ETAPS 2016.
- Michaël Rusinowitch: ACM International Workshop on Security And Privacy Analytics, New Orleans, LA, USA, March 11, 2016. (co-chair with Rakesh Verma, U. Houston).

10.1.1.3. Program Committee Member

- Véronique Cortier: LICS 2017, CCS 2016, Concur 2016, E-VoteID 2016, MFCS 2016, EuroS&P 2016.
- Steve Kremer : Voting 2017, Euro S&P 2017, FSTTCS 2016, ESORICS 2016, CSF 2016, Voting 2016, AsiaCCS 2016, ACISP 2016.
- Christophe Ringeissen: FroCoS 2017, UNIF 2017, WRLA 2016, UNIF 2016, IJCAR 2016.
- Michaël Rusinowitch: POST 2016, CRISIS 2016, STM 2016.
- Vincent Cheval: TMPA 2017

10.1.2. Journal

10.1.2.1. Editorial Board Member

- Véronique Cortier: Information & Computation, Journal of Computer Security, ACM Transactions on Information and System Security (TISSEC), Foundations and Trends (FnT) in Security and Privacy.

10.1.2.2. Scientific Committee Member

- Laurent Vigneron: Technique et Sciences Informatiques, Lavoisier.

10.1.3. Invited Talks

- Steve Kremer: 29th IEEE Computer Security Foundations Symposium (CSF'16).

10.1.4. Research Administration

Inria evaluation committee (Steve Kremer)

[0] https://www.legifrance.gouv.fr/affichCnil.do?id=CNILTEXT000023174487

Jury Junior Research Position Inria Rennes-Bretagne Atlantique (Steve Kremer)

Jury Senior Research Position (Steve Kremer)

Jury Junior Research Position Inria Nancy-Grand Est (Véronique Cortier, president of the committee)

Jury Professor at Université de Lorraine (Véronique Cortier)

Jury Assistant Professor at Université de Lorraine (Michaël Rusinowitch)

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

- Licence:

  Vincent Cheval, Introduction to Theoretical Computer Science (Logic, Languages, Automata), 69 hours (ETD), TELECOM Nancy.

  Jannik Dreier, Introduction to Theoretical Computer Science (Logic, Languages, Automata), 146 hours (ETD), TELECOM Nancy.

- Master:

  Véronique Cortier, Security of flows, 20 hours, M2 Computer Science, Telecom Nancy and Mines Nancy, France.

  Abdessamad Imine, Security for XML Documents, 12 hours (ETD), M1, Lorraine University, France.

  Steve Kremer, Security Theory, 24 hours (ETD), M2 Computer science, Lorraine University, France.

  Christophe Ringeissen, Decision Procedures for Software Verification, 18 hours (ETD), M2 Computer science, Lorraine University, France.

  Laurent Vigneron, Security of information systems, 22.5 hours (ETD), M2 Computer science, Lorraine University, France.

  Laurent Vigneron, Security of information systems, 24 hours (ETD), M2 MIAGE – Distributed Information Systems, Lorraine University, France.

  Laurent Vigneron, Security of information systems, 16 hours (ETD), M2 MIAGE – Audit and Design of Information Systems, Lorraine University, France.

10.2.2. Supervision

- HDR defended in 2016:

  Abdessamad Imine, Data sharing in collaborative systems, defended on December 9.

- PhD defended in 2016:

  Rémy Chrétien, Decision procedures of equivalence properties, started in October 2012, Véronique Cortier and Stéphanie Delaune
  Huu Hiep Nguyen, Secure Collaboration in Mobile Social Networks, started in November 2013, Abdessamad Imine and Michaël Rusinowitch

- PhD discontinued in 2016:

  Éric Le Morvan, Secure composition of cryptographic protocols, started in October 2013, discontinued in June 2016, Véronique Cortier

- PhD in progress:

  Younes Abid, Privacy control for social networks, started in March 2015. Abdessamad Imine, Michaël Rusinowitch and Orpailleur co-advising.

  Antoine Dallon, Decision procedures for equivalence properties, started in November 2015, Véronique Cortier and Stéphanie Delaune

Alicia Filipiak, Design and validation of security services for mobile platforms: smartphones and tablets, started in March 2015, Véronique Cortier

Joseph Lallemand, Type systems for equivalence properties, started in September 2016, Véronique Cortier

Ludovic Robin, Verification of cryptographic protocols using weak secrets, started in October 2014, Stéphanie Delaune and Steve Kremer

10.2.3. Juries

Reviewer for Yang Zhang PhD, Luxembourg (Michaël Rusinowitch)

Examiner for Stefania Dumbrova, Paris-Sud (Michaël Rusinowitch)

Examiner for Jiri Marsik, LORIA (Laurent Vigneron)

Examiner for Robin David, CEA (Steve Kremer)

10.3. Popularization

- Vote Électronique. Véronique Cortier. 1024 – Bulletin de la société informatique de France. Numéro 9, Novembre 2016.
- How to Explain Modern Security Concepts to your Children. Xavier Bultel, Jannik Dreier, Pascal Lafourcade, Malika More. Cryptologia, Taylor & Francis, 2016. [13]
- Comment sécuriser les communications ? Du bon usage des protocoles et de la cryptographie. Vincent Cheval, Joseph Lallemand – Séminaire *La Pépinière 4.1*, Oct 2016, Maisons pour la science au service des professeurs, Nancy.

11. Bibliography

Major publications by the team in recent years

[1] W. Belkhir, Y. Chevalier, M. Rusinowitch. *Parametrized automata simulation and application to service composition*, in "J. Symb. Comput.", 2015, vol. 69, p. 40–60.

[2] D. Bernhard, V. Cortier, D. Galindo, O. Pereira, B. Warinschi. *A comprehensive analysis of game-based ballot privacy definitions*, in "Proceedings of the 36th IEEE Symposium on Security and Privacy (S&P'15)", IEEE Computer Society Press, May 2015, p. 499–516.

[3] R. Chadha, S. Ciobaca, S. Kremer. *Automated Verification of Equivalence Properties of Cryptographic Protocols*, in "Programming Languages and Systems - 21st European Symposium on Programming, ESOP 2012, Held as Part of the European Joint Conferences on Theory and Practice of Software, ETAPS 2012, Tallinn, Estonia, March 24 - April 1, 2012. Proceedings", H. Seidl (editor), Lecture Notes in Computer Science, Springer, 2012, vol. 7211, p. 108–127.

[4] P. Chocron, P. Fontaine, C. Ringeissen. *A Polite Non-Disjoint Combination Method: Theories with Bridging Functions Revisited*, in "Proceedings of the 25th International Conference on Automated Deduction (CADE-25)", Lecture Notes in Computer Science, Springer, August 2015, vol. 9195, p. 419-433, https://hal.inria.fr/hal-01157898.

[5] R. Chretien, V. Cortier, S. Delaune. *Typing messages for free in security protocols: the case of equivalence properties*, in "Proceedings of the 25th International Conference on Concurrency Theory (CONCUR'14)", Rome, Italy, Lecture Notes in Computer Science, Springer, September 2014, vol. 8704, p. 372-386.

[6] S. KREMER, R. KÜNNEMANN.*Automated Analysis of Security Protocols with Global State*, in "2014 IEEE Symposium on Security and Privacy, SP 2014, Berkeley, CA, USA, May 18-21, 2014", IEEE Computer Society, 2014, p. 163–178.

[7] H. H. NGUYEN, A. IMINE, M. RUSINOWITCH.*Anonymizing Social Graphs via Uncertainty Semantics*, in "Proceedings of the 10th ACM Symposium on Information, Computer and Communications Security, (ASIA CCS'15), 2015", ACM, 2015, p. 495–506.

Publications of the year

Doctoral Dissertations and Habilitation Theses

[8] R. CHRETIEN.*Automated analysis of equivalence properties for cryptographic protocols*, Université Paris-Saclay, January 2016, https://tel.archives-ouvertes.fr/tel-01277205.

[9] H.-H. NGUYEN.*Social Graph Anonymization*, Universite de Lorraine, November 2016, https://hal.inria.fr/tel-01403474.

Articles in International Peer-Reviewed Journal

[10] T. ABBES, A. BOUHOULA, M. RUSINOWITCH.*Detection of firewall configuration errors with updatable tree*, in "International Journal of Information Security", June 2016, vol. 15, n^o^ 3, p. 301-317 [*DOI :* 10.1007/S10207-015-0290-0], https://hal.inria.fr/hal-01320646.

[11] T. AVANESOV, Y. CHEVALIER, M. RUSINOWITCH, M. TURUANI.*Intruder deducibility constraints with negation. Decidability and application to secured service compositions*, in "Journal of Symbolic Computation", 2017, vol. 80, p. 4 - 26 [*DOI :* 10.1016/J.JSC.2016.07.008], https://hal.inria.fr/hal-01405851.

[12] T. AVANESOV, Y. CHEVALIER, M. RUSINOWITCH, M. TURUANI.*Satisfiability of General Intruder Constraints with and without a Set Constructor*, in "Journal of Symbolic Computation", 2017, vol. 80, p. 27-61 [*DOI :* 10.1016/J.JSC.2016.07.009], https://hal.inria.fr/hal-01405842.

[13] X. BULTEL, J. DREIER, P. LAFOURCADE, M. MORE.*How to Explain Modern Security Concepts to your Children*, in "Cryptologia", November 2016, https://hal.archives-ouvertes.fr/hal-01397035.

[14] R. CHADHA, V. CHEVAL, Ş. C. CIOBÂCĂ, S. KREMER.*Automated verification of equivalence properties of cryptographic protocols*, in "ACM Transactions on Computational Logic", 2016, vol. 17, n^o^ 4 [*DOI :* 10.1145/2926715], https://hal.inria.fr/hal-01306561.

[15] S. KREMER, R. KÜNNEMANN.*Automated Analysis of Security Protocols with Global State*, in "Journal of Computer Security", 2016, vol. 24, n^o^ 5 [*DOI :* 10.3233/JCS-160556], https://hal.inria.fr/hal-01351388.

[16] H. NGUYEN, A. IMINE, M. RUSINOWITCH.*Network Structure Release under Differential Privacy*, in "Transactions on Data Privacy", December 2016, vol. 9, n^o^ 3, 26, https://hal.inria.fr/hal-01424911.

[17] J. YU, V. CHEVAL, M. RYAN.*DTKI: A New Formalized PKI with Verifiable Trusted Parties*, in "The Computer Journal", 2016, vol. 59, p. 1695-1713 [*DOI :* 10.1093/COMJNL/BXW039], https://hal.archives-ouvertes.fr/hal-01403899.

International Conferences with Proceedings

[18] Y. ABID, A. IMINE, A. NAPOLI, C. RAÏSSI, M. RUSINOWITCH.*Online link disclosure strategies for social networks*, in "The 11th International Conference on Risks and Security of Internet and Systems", Roscoff, France, The 11th International Conference on Risks and Security of Internet and Systems, September 2016, https://hal.inria.fr/hal-01402062.

[19] M. ARAPINIS, V. CORTIER, S. KREMER.*When are three voters enough for privacy properties?*, in "21st European Symposium on Research in Computer Security", Heraklion, Crete, Greece, 21st European Symposium on Research in Computer Security, Springer, 2016, https://hal.inria.fr/hal-01351398.

[20] M. BACKES, J. DREIER, S. KREMER, R. KÜNNEMANN. *A Novel Approach for Reasoning about Liveness in Cryptographic Protocols and its Application to Fair Exchange*, in "2nd IEEE European Symposium on Security and Privacy (EuroS&P'17)", Paris, France, Proceedings of the 2nd IEEE European Symposium on Security and Privacy, Springer, 2017, https://hal.inria.fr/hal-01396282.

[21] R. BERTHON, C. RINGEISSEN.*Satisfiability Modulo Free Data Structures Combined with Bridging Functions*, in "14th International Workshop on Satisfiability Modulo Theories, affiliated with IJCAR 2016", Coimbra, Portugal, T. KING, R. PISKAC (editors), CEUR Workshop Proceedings, CEUR-WS.org, July 2016, n^{o} 1617, p. 71–80, https://hal.inria.fr/hal-01389228.

[22] X. BULTEL, J. DREIER, J.-G. DUMAS, P. LAFOURCADE.*Physical Zero-Knowledge Proofs for Akari, Takuzu, Kakuro and KenKen*, in "FUN with algorithms 2016", La Maddalena, Italy, E. DEMAINE, F. GRANDONI (editors), FUN with algorithms 2016, June 2016, https://hal.archives-ouvertes.fr/hal-01326059.

[23] P. CHAIDOS, V. CORTIER, G. FUCHSBAUER, D. GALINDO.*BeleniosRF: A Non-interactive Receipt-Free Electronic Voting Scheme*, in "23rd ACM Conference on Computer and Communications Security (CCS'16)", Vienna, Austria, October 2016 [*DOI :* 10.1145/2976749.2978337], https://hal.inria.fr/hal-01377917.

[24] *Best Paper*
V. CORTIER, A. DALLON, S. DELAUNE.*Bounding the number of agents, for equivalence too*, in "5th International Conference on Principles of Security and Trust (POST'16)", Eindhoven, Netherlands, April 2016, p. 211-232 [*DOI :* 10.1007/978-3-662-49635-0_11], https://hal.inria.fr/hal-01361286.

[25] V. CORTIER, A. FILIPIAK, S. GHAROUT, J. TRAORÉ.*Designing and proving an EMV-compliant payment protocol for mobile devices*, in "2nd IEEE European Symposium on Security and Privacy (EuroSP'17)", Paris, France, April 2017, https://hal.inria.fr/hal-01408584.

[26] V. CORTIER, D. GALINDO, R. KUESTERS, J. MUELLER, T. TRUDERUNG.*SoK: Verifiability Notions for E-Voting Protocols*, in "36th IEEE Symposium on Security and Privacy (S&P'16)", San Jose, United States, May 2016, https://hal.inria.fr/hal-01280445.

[27] C. JACOMME, S. KREMER, G. SCERRI.*Symbolic Models for Isolated Execution Environments*, in "2nd IEEE European Symposium on Security and Privacy (EuroS&P'17)", Paris, France, Proceedings of the 2nd IEEE European Symposium on Security and Privacy, Springer, 2017, https://hal.inria.fr/hal-01396291.

[28] S. KREMER, P. RØNNE.*To Du or not to Du: A Security Analysis of Du-Vote*, in "IEEE European Symposium on Security and Privacy 2016", Saarbrucken, Germany, Proceedings of the IEEE European Symposium on Security and Privacy 2016, IEEE Computer Society, March 2016, https://hal.inria.fr/hal-01238894.

[29] H. H. NGUYEN, A. IMINE, M. RUSINOWITCH.*Detecting Communities under Differential Privacy*, in "Workshop on Privacy in the Electronic Society - WPES 206", Vienna, Austria, October 2016, p. 83 - 93, https://hal.inria.fr/hal-01393266.

Conferences without Proceedings

[30] M. TURUANI, T. VOEGTLIN, M. RUSINOWITCH.*Automated Verification of Electrum Wallet*, in "3rd Workshop on Bitcoin and Blockchain Research", Christ Church, Barbados, February 2016, https://hal.inria.fr/hal-01256397.

Books or Proceedings Editing

[31] R. VERMA, M. RUSINOWITCH (editors). *International Workshop on Security And Privacy Analytics*, IWSPA '16: Proceedings of the 2016 ACM on International Workshop on Security And Privacy Analytics, ACM, New Orleans, United States, 2016, https://hal.inria.fr/hal-01408625.

References in notes

[32] M. ARAPINIS, V. CORTIER, S. KREMER, M. RYAN.*Practical Everlasting Privacy*, in "Principles of Security and Trust - Second International Conference, POST 2013, Held as Part of the European Joint Conferences on Theory and Practice of Software, ETAPS 2013, Rome, Italy, March 16-24, 2013. Proceedings", D. BASIN, J. MITCHELL (editors), Lecture Notes in Computer Science, Springer, 2013, vol. 7796, p. 21–40.

[33] M. ARAPINIS, L. MANCINI, E. RITTER, M. RYAN, N. GOLDE, K. REDON, R. BORGAONKAR.*New privacy issues in mobile telephony: fix and verification*, in "Proc. 19th ACM Conference on Computer and Communications Security (CCS'12)", ACM Press, 2012, p. 205-216.

[34] B. BLANCHET.*An Efficient Cryptographic Protocol Verifier Based on Prolog Rules*, in "Proc. 14th Computer Security Foundations Workshop (CSFW'01)", IEEE Comp. Soc. Press, 2001, p. 82–96.

[35] M. BORTOLOZZO, M. CENTENARO, R. FOCARDI, G. STEEL.*Attacking and Fixing PKCS#11 Security Tokens*, in "Proc. 17th ACM Conference on Computer and Communications Security (CCS'10)", ACM Press, 2010, p. 260-269.

[36] C. CHEVALIER, S. DELAUNE, S. KREMER, M. RYAN.*Composition of Password-based Protocols*, in "Formal Methods in System Design", 2013, vol. 43, p. 369-413.

[37] Y. CHEVALIER, L. VIGNERON.*Strategy for Verifying Security Protocols with Unbounded Message Size*, in "Journal of Automated Software Engineering", April 2004, vol. 11, n^{o} 2, p. 141-166.

[38] H. COMON-LUNDH, S. DELAUNE.*The finite variant property: How to get rid of some algebraic properties*, in "Proc. of the 16th International Conference on Rewriting Techniques and Applications (RTA'05)", LNCS, Springer, 2005, vol. 3467, p. 294-307.

[39] V. CORTIER, S. DELAUNE.*Safely Composing Security Protocols*, in "Formal Methods in System Design", February 2009, vol. 34, n^{o} 1, p. 1-36.

[40] S. DELAUNE, S. KREMER, M. RYAN.*Verifying Privacy-type Properties of Electronic Voting Protocols*, in "Journal of Computer Security", July 2009, vol. 17, n^{o} 4, p. 435-487.

[41] S. DELAUNE, S. KREMER, G. STEEL.*Formal Analysis of PKCS#11 and Proprietary Extensions*, in "Journal of Computer Security", November 2010, vol. 18, n^{o} 6, p. 1211-1245.

[42] S. ERBATUR, D. KAPUR, A. M. MARSHALL, C. MEADOWS, P. NARENDRAN, C. RINGEISSEN.*On Asymmetric Unification and the Combination Problem in Disjoint Theories*, in "Proc. 17th International Conference on Foundations of Software Science and Computation Structures (FoSSaCS'14)", LNCS, Springer, 2014, p. 274-288.

[43] S. ESCOBAR, C. MEADOWS, J. MESEGUER.*Maude-NPA: Cryptographic Protocol Analysis Modulo Equational Properties*, in "Foundations of Security Analysis and Design V", LNCS, Springer, 2009, vol. 5705, p. 1-50.

[44] D. GOLLMANN.*What do we mean by entity authentication?*, in "Proc. Symposium on Security and Privacy (SP'96)", IEEE Comp. Soc. Press, 1996, p. 46–54.

[45] G. GREWAL, M. RYAN, L. CHEN, M. CLARKSON.*Du-Vote: Remote Voting with Untrusted Computers*, in "Proc. 28th IEEE Computer Security Foundations Symposium (CSF'11)", IEEE Computer Society Press, 2015.

[46] J. HERZOG.*Applying protocol analysis to security device interfaces*, in "IEEE Security & Privacy Magazine", July-Aug 2006, vol. 4, n^{o} 4, p. 84–87.

[47] B. SCHMIDT, S. MEIER, C. CREMERS, D. BASIN.*The TAMARIN Prover for the Symbolic Analysis of Security Protocols*, in "Proc. 25th International Conference on Computer Aided Verification (CAV'13)", LNCS, Springer, 2013, vol. 8044, p. 696-701.

[48] V. SOFRONIE-STOKKERMANS.*Locality Results for Certain Extensions of Theories with Bridging Functions*, in "Automated Deduction - CADE-22, 22nd International Conference on Automated Deduction, Montreal, Canada, August 2-7, 2009. Proceedings", R. A. SCHMIDT (editor), Lecture Notes in Computer Science, Springer, 2009, vol. 5663, p. 67–83.

Project-Team SEMAGRAMME

Semantic Analysis of Natural Language

IN COLLABORATION WITH: Laboratoire lorrain de recherche en informatique et ses applications (LORIA)

IN PARTNERSHIP WITH:
CNRS

Université de Lorraine

RESEARCH CENTER
Nancy - Grand Est

THEME
Language, Speech and Audio

Table of contents

Project-Team SEMAGRAMME

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

Keywords:

Computer Science and Digital Science:

5.8. - Natural language processing
7.4. - Logic in Computer Science
8.4. - Natural language processing

Other Research Topics and Application Domains:

9.5.8. - Linguistics

1. Members

Research Scientists

Philippe de Groote [Team leader, Inria, Senior Researcher]
Bruno Guillaume [Inria, Researcher]
Sylvain Pogodalla [Inria, Researcher]

Faculty Members

Maxime Amblard [Univ. Lorraine, Associate Professor, HDR]
Guy Perrier [Univ. Lorraine, Professor emeritus, HDR]

Technical Staff

Nicolas Lefebvre [Inria]

PhD Students

Clément Beysson [Univ. Lorraine]
Jirka Maršík [Inria]
Aleksandre Maskharashvili [Inria, granted by ANR POLYMNIE project]

Administrative Assistants

Antoinette Courrier [CNRS]
Sylvie Musilli [Univ. Lorraine]
Céline Simon [Inria]

Others

Alexandre Bertrand [Univ. Lorraine, Intern, May 2016]
Pierre Ludmann [ENS Cachan, Intern, from March 2016 to July 2016]
Alice Millour [Inria, Intern, from July 2016 to August 2016]
Stéphane Tiv [Univ. Lorraine, Intern, from February 2016 to June 2016]
Anh Duc Vu [Univ. Lorraine, Intern, from February 2016 to June 2016]

2. Overall Objectives

2.1. Scientific context

Computational linguistics is a discipline at the intersection of computer science and linguistics. On the theoretical side, it aims to provide computational models of the human language faculty. On the applied side, it is concerned with natural language processing and its practical applications.

From a structural point of view, linguistics is traditionally organized into the following sub-fields:

- Phonology, the study of language abstract sound systems.
- Morphology, the study of word structure.
- Syntax, the study of language structure, i.e., the way words combine into grammatical phrases and sentences.
- Semantics, the study of meaning at the levels of words, phrases, and sentences.
- Pragmatics, the study of the ways in which the meaning of an utterance is affected by its context.

Computational linguistics is concerned by all these fields. Consequently, various computational models, whose application domains range from phonology to pragmatics, have been developed. Among these, logic-based models play an important part, especially at the "higher" levels.

At the level of syntax, generative grammars [31] may be seen as basic inference systems, while categorial grammars [43] are based on substructural logics specified by Gentzen sequent calculi. Finally, model-theoretic grammars [56] amount to sets of logical constraints to be satisfied.

At the level of semantics, the most common approaches derive from Montague grammars [46], [47], [48], which are based on the simply typed λ-calculus and Church's simple theory of types [32]. In addition, various logics (modal, hybrid, intensional, higher-order...) are used to express logical semantic representations.

At the level of pragmatics, the situation is less clear. The word *pragmatics* has been introduced by Morris [50] to designate the branch of philosophy of language that studies, besides linguistic signs, their relation to their users and the possible contexts of use. The definition of pragmatics was not quite precise, and for a long time several authors have considered (and some authors are still considering) pragmatics as the wastebasket of syntax and semantics [27]. Nevertheless, as far as discourse processing is concerned (which includes pragmatic problems such as pronominal anaphora resolution), logic-based approaches have also been successful. In particular, Kamp's Discourse Representation Theory [41] gave rise to sophisticated 'dynamic' logics [40]. The situation, however, is less satisfactory than it is at the semantic level. On the one hand, we are facing a kind of logical "tower of Babel". The various pragmatic logic-based models that have been developed, while sharing underlying mathematical concepts, differ in several respects and are too often based on *ad hoc* features. As a consequence, they are difficult to compare and appear more as competitors than as collaborative theories that could be integrated. On the other hand, several phenomena related to discourse dynamics (e.g., context updating, presupposition projection and accommodation, contextual reference resolution...) are still lacking deep logical explanations. We strongly believe, however, that this situation can be improved by applying to pragmatics the same approach Montague applied to semantics, using the standard tools of mathematical logic.

Accordingly:

> *The overall objective of the Sémagramme project is to design and develop new unifying logic-based models, methods, and tools for the semantic analysis of natural language utterances and discourses. This includes the logical modeling of pragmatic phenomena related to discourse dynamics. Typically, these models and methods will be based on standard logical concepts (stemming from formal language theory, mathematical logic, and type theory), which should make them easy to integrate.*

The project is organized along three research directions (i.e., *Syntax-semantics interface*, *Discourse dynamics*, and *Common basic resources*), which interact as explained below.

2.2. Syntax-semantics interface

The Sémagramme project intends to focus on the semantics of natural languages (in a wider sense than usual, including some pragmatics). Nevertheless, the semantic construction process is syntactically guided, that is, the constructions of logical representations of meaning are based on the analysis of the syntactic structures. We do not want, however, to commit ourselves to such or such specific theory of syntax. Consequently, our approach should be based on an abstract generic model of the syntax-semantic interface.

Here, an important idea of Montague comes into play, namely, the "homomorphism requirement": semantics must appear as a homomorphic image of syntax. While this idea is almost a truism in the context of mathematical logic, it remains challenged in the context of natural languages. Nevertheless, Montague's idea has been quite fruitful, especially in the field of categorial grammars, where van Benthem showed how syntax and semantics could be connected using the Curry-Howard isomorphism [61]. This correspondence is the keystone of the syntax-semantics interface of modern type-logical grammars [49]. It also motivated the definition of our own Abstract Categorial Grammars [3].

Technically, an Abstract Categorial Grammar simply consists of a (linear) homomorphism between two higher-order signatures. Extensive studies have shown that this simple model allows several grammatical formalisms to be expressed, providing them with a syntax-semantics interface for free [4], [59], [60], [54], [42], [55].

We intend to carry on with the development of the Abstract Categorial Grammar framework. At the foundational level, we will define and study possible type theoretic extensions of the formalism, in order to increase its expressive power and its flexibility. At the implementation level, we will continue the development of an Abstract Categorial Grammar support system.

As said above, to consider the syntax-semantics interface as the starting point of our investigations allows us not to be committed to some specific syntactic theory. The Montagovian syntax-semantics interface, however, cannot be considered to be universal. In particular, it does not seem to be that well adapted to dependency and model-theoretic grammars. Consequently, in order to be as generic as possible, we intend to explore alternative models of the syntax-semantics interface. In particular, we will explore relational models where several distinct semantic representations can correspond to the same syntactic structure.

2.3. Discourse dynamics

It is well known that the interpretation of a discourse is a dynamic process. Take a sentence occurring in a discourse. On the one hand, it must be interpreted according to its context. On the other hand, its interpretation affects this context, and must therefore result in an updating of the current context. For this reason, discourse interpretation is traditionally considered to belong to pragmatics. The cut between pragmatics and semantics, however, is not that clear.

As we mentioned above, we intend to apply to some aspects of pragmatics (mainly, discourse dynamics) the same methodological tools Montague applied to semantics. The challenge here is to obtain a completely compositional theory of discourse interpretation, by respecting Montague's homomorphism requirement. We think that this is possible by using techniques coming from programming language theory, in particular, continuation semantics [58], [28], [29], [57] and the related theories of functional control operators [35], [36].

We have indeed successfully applied such techniques in order to model the way quantifiers in natural languages may dynamically extend their scope [5]. We intend to tackle, in a similar way, other dynamic phenomena (typically, anaphora and referential expressions, presupposition, modal subordination...).

What characterize these different dynamic phenomena is that their interpretations need information to be retrieved from a current context. This raises the question of the modeling of the context itself. At a foundational level, we have to answer questions such as the following. What is the nature of the information to be stored in the context? What are the processes that allow implicit information to be inferred from the context? What are the primitives that allow a context to be updated? How does the structure of the discourse and the discourse relations affect the structure of the context? These questions also raise implementation issues. What are the appropriate datatypes? How can we keep the complexity of the inference algorithms sufficiently low?

2.4. Common basic resources

Even if our research primarily focuses on semantics and pragmatics, we nevertheless need syntax. More precisely, we need syntactic trees to start with. We consequently need grammars, lexicons and parsing algorithms to produce such trees. During the last years, we have developed the notion of interaction grammar [2] as a model of natural language syntax. This includes the development of a grammar for French [53], together with morpho-syntactic lexicons. We intend to continue this line of research and development. In particular, we want to increase the coverage of our French grammar, and provide our parser with more robust algorithms.

Further primary resources are needed in order to put at work a computational semantic analysis of utterances and discourses. As we want our approach to be as compositional as possible, we must develop lexicons annotated with semantic information. This opens the quite wide research area of lexical semantics.

Finally, when dealing with logical representations of utterance interpretations, the need for inference facilities is ubiquitous. Inference is needed in the course of the interpretation process, but also to exploit the result of the interpretation. Indeed, an advantage of using formal logic for semantic representations is the possibility of using logical inference to derive new information. From a computational point of view, however, logical inference may be highly complex. Consequently, we need to investigate which logical fragments can be used efficiently for natural language oriented inference.

3. Research Program

3.1. Overview

The Sémagramme project relies on deep mathematical foundations. We intend to develop models based on well-established mathematics. We seek two main advantages from this approach. On the one hand, by relying on mature theories, we have at our disposal sets of mathematical tools that we can use to study our models. On the other hand, developing various models on a common mathematical background will make them easier to integrate, and will ease the search for unifying principles.

The main mathematical domains on which we rely are formal language theory, symbolic logic, and type theory.

3.2. Formal language theory

Formal language theory studies the purely syntactic and combinatorial aspects of languages, seen as sets of strings (or possibly trees or graphs). Formal language theory has been especially fruitful for the development of parsing algorithms for context-free languages. We use it, in a similar way, to develop parsing algorithms for formalisms that go beyond context-freeness. Language theory also appears to be very useful in formally studying the expressive power and the complexity of the models we develop.

3.3. Symbolic logic

Symbolic logic (and, more particularly, proof-theory) is concerned with the study of the expressive and deductive power of formal systems. In a rule-based approach to computational linguistics, the use of symbolic logic is ubiquitous. As we previously said, at the level of syntax, several kinds of grammars (generative, categorial...) may be seen as basic deductive systems. At the level of semantics, the meaning of an utterance is captured by computing (intermediate) semantic representations that are expressed as logical forms. Finally, using symbolic logics allows one to formalize notions of inference and entailment that are needed at the level of pragmatics.

3.4. Type theory and typed λ-calculus

Among the various possible logics that may be used, Church's simply typed λ-calculus and simple theory of types (a.k.a. higher-order logic) play a central part. On the one hand, Montague semantics is based on the simply typed λ-calculus, and so is our syntax-semantics interface model. On the other hand, as shown by Gallin [39], the target logic used by Montague for expressing meanings (i.e., his intensional logic) is essentially a variant of higher-order logic featuring three atomic types (the third atomic type standing for the set of possible worlds).

4. Application Domains

4.1. Deep semantic analysis

Our applicative domains concern natural language processing applications that rely on a deep semantic analysis. For instance, one may cite the following ones:

- textual entailment and inference,
- dialogue systems,
- semantic-oriented query systems,
- content analysis of unstructured documents,
- text transformation and automatic summarization,
- (semi) automatic knowledge acquisition.

It seems clear, nowadays, that the need for semantics is ubiquitous. Nevertheless, according to the present state of the art, there are only a few applications for which a deep semantic analysis results in a real improvement over non semantic-based techniques. This is due to the fact that most current application chains are such that their weakest links are not located at the semantic level.

4.2. Text Transformation

Text transformation is an application domain featuring two important sub-fields of computational linguistics:

- parsing, from surface form to abstract representation,
- generation, from abstract representation to surface form.

Text simplification or automatic summarization belong to that domain.

We aim at using the framework of Abstract Categorial Grammars we develop to this end. It is indeed a reversible framework that allows both parsing and generation. Its underlying mathematical structure of λ-calculus makes it fit with our type-theoretic approach to discourse dynamics modeling. The ANR project Polymnie (see section 7.2.1.1) is especially dedicated to this aim.

5. New Software and Platforms

5.1. ACGtk

Abstract Categorial Grammar Development Toolkit
KEYWORDS: Natural language processing - NLP - Syntactic analysis - Semantics
FUNCTIONAL DESCRIPTION

ACGtk provides softwares for developing and using Abstract Categorial Grammars (ACG).

- Contact: Sylvain Pogodalla
- URL: http://www.loria.fr/equipes/calligramme/acg/

5.2. Grew

Graph Rewriting
FUNCTIONAL DESCRIPTION

Grew is a Graph Rewriting tool dedicated to applications in NLP. Grew takes into account confluent and non-confluent graph rewriting and it includes several mechanisms that help to use graph rewriting in the context of NLP applications (built-in notion of feature structures, parametrization of rules with lexical information).

In 2016, Grew was used in different applications. The Graph Rewriting System presented in [1] was improved and is used in the preprocessing of data in the ZombiLingo project (see 6.3.1). It was also extensively used in the Universal Dependencies project for improving the French sub-corpus.

- Contact: Bruno Guillaume
- URL: http://grew.loria.fr

5.3. ZombiLingo

FUNCTIONAL DESCRIPTION

ZombiLingo is a GWAP (Game With A Purpose) where gamers have to give linguistic information about the syntax of natural language sentence.

During 2016, the main evolutions of the application were:

- New game modes: for instance the duel mode where two players can compare their results on a set on sentence.
- Integration of data preprocessing, data postprocessing to the back-office.
- Integration of evaluation methods [15] in the back-office.

The current version is used for the French language and it is planned to use it with other languages (English and low-resourced languages).

- Authors: Nicolas Lefebvre, Karën Fort, Bruno Guillaume and Valentin Stern
- Contact: Bruno Guillaume
- Application URL: http://zombilingo.org/
- Code URL: https://github.com/zombilingo

5.4. SLAMtk

A management chain of the transcriptions of interviews for the SLAM project which products of a full anonymized randomized version of the resources. Some extensions have been implemented based on Distagger (disfluences) and MElt (POS and lemma). The tool was reimplemented in order to propose generic treatments for the different corpora.

- Contact: Maxime Amblard
- URL: http://slam.loria.fr

6. New Results

6.1. Syntax-semantics interface

Participants: Philippe de Groote, Sylvain Pogodalla.

6.1.1. Lambek categorial grammar as abstract categorial grammars

Abstract Categorial Grammars (ACG, for short) differ from classical categorial grammars in an essential way: the ACG type system is based on a commutative logic (namely, the implicative fragment of multiplicative linear logic). For this reason, it has been argued that the way of encoding wh-extraction in an ACG corresponds to an uncontrolled form of extraction, which results in syntactic overgeneration. In particular, an ACG could not accomodate left and right peripheral extractions like a Lambek categorial grammar (LG, for short) does. In order to challenge this claim, we have shown how LG may be encoded as ACG [14].

6.1.2. Lexical Semantics

The interpretation of natural language utterances relies on two complementary elements of natural language modeling. On the one hand, the description of the combinatorics of natural language expresses how elementary units, or *lexical units* (typically the word), combine in order to build more complex elements, such as sentences or discourses. On the other hand, the description of these elementary units specifies how they contribute to the meaning of the whole by their *lexical meaning*. This specification should also take into account how the different parts of the lexical meanings combine during the *composition* process and how they relate to their underlying meaning concepts. For instance, the verbs *buy* and *sell* should refer to a common conceptual representation. However, their syntactic arguments (e.g., the subject) play a different (semantic) role with respect to the *transaction* concept that they share.

The modeling of these concepts and how they relate to each other gave rise to Frames Semantics as a representation format of conceptual and lexical knowledge [37], [30], [25], [45]. Frames consists of directed graphs where nodes correspond to entities (individuals, events, ...) and edges correspond to (functional or non-functional) relations between these entities. Providing a fine-grained representation of the internal concept structure allows both for a *decomposition* of the lexical meaning and for a precise description of the sub-structural interactions in the semantic composition process [44].

Following up on our previous work based on Hybrid Logic (HL) [26], [24] on linking Frames and truth-logical semantics, with a specific focus on explicit quantification over entities or events that are lexically triggered, we extended our model to the interaction between bounded events and *for*-adverbials. This interaction turns bounded events (*John biked to the office*) to iterated events (*John biked to the office for three months*), when the bounded events themselves result from coercing a progression (*John biked*) by addition of a prepositional phrase (*to the office*). We also proposed a modeling taking into account the respective scopes of the quantifiers induced by *for*-adverbials (over events) and quantification introduced by indefinites (over entities) [17]. Finally, we used the flexibility of the approach to model semantic coercion as induced by verbs such as *read* that can syntactically have an entity as argument (*John began a book*) while it semantically relates to an event (e.g., *reading*, *writing*, etc.) [21].

6.2. Discourse dynamics

Participants: Philippe de Groote, Sylvain Pogodalla, Maxime Amblard, Jirka Maršík, Aleksandre Maskharashvili.

6.2.1. Effects and Handlers in Natural Language

In formal semantics, logical meanings are assigned to natural language utterances. This process is guided by the principle of compositionality: the meaning of an expression is a function of the meanings of its parts. These functions are often formalized using the λ-calculus. However, there are areas of language which challenge the notion of compositionality, e.g. anaphoric pronouns or presupposition triggers. These force one to either abandon compositionality or adjust the structure of meanings. In the first case, meanings are derived by processes that no longer correspond to pure mathematical functions but rather to context-sensitive procedures, much like the functions of a programming language that manipulate their context with side effects. In the second case, when the structure of meanings is adjusted, the new meanings tend to be instances of the same mathematical structure, the monad. Monads themselves being widely used in functional programming to encode side effects, the common theme that emerges in both approaches is the introduction of side effects. Furthermore, different problems in semantics lead to different theories which are challenging to unite. We claim that by looking at these theories as theories of side effects, we can reuse results from programming language research to combine them.

Our work extends the λ-calculus with a monad of computations. The monad implements effects and handlers, a recent technique in the study of programming language side effects. We have proven some of the fundamental properties of our extended calculus: subject reduction, confluence and termination. We have then demonstrated how to use our calculus to implement treatments of several linguistic phenomena: deixis, quantification, conventional implicature, anaphora and presupposition.

6.2.2. Discourse Modeling with Abstract Categorial Grammars

We have studied several TAG-based grammatical formalisms for discourse analysis (D-LTAG [38], G-TAG [34], and D-STAG [33]), and we have proposed an ACG encodings of them. G-TAG is a formalism introduced for generating natural language texts out of conceptual (semantic) representation inputs. D-STAG is a synchronous formalism for modeling the syntax-semantics interface for discourse. It was introduced for discourse analysis (parsing). The ACG encodings of G-TAG and D-STAG shed light on the problem of clause-medial connectives that TAG-based formalisms do not account for. To deal with a discourse that contains clause-medial connectives, D-LTAG, G-TAG, and D-STAG, all make use of an extra grammatical step. In contrast, the ACG encodings of G-TAG and D-STAG offer a purely grammatical approach to discourse connectives occupying clause-medial positions. The method we propose is a generic one and can serve as a solution for encoding clause-medial connectives with the formalisms based on TAGs. The ACG encodings of G-TAG and D-STAG that we propose are second-order. Importantly, the class of second-order ACGs consists of intrinsically reversible grammars. Grammars of this class use the same polynomial algorithm to build parse structures both for strings and for logical formulas. Thus, second-order ACGs can be used both for parsing and generation. Therefore, the problems of parsing and generation with the ACG encodings of G-TAG and D-STAG are of polynomial complexity.

6.3. Common basic resources

Participants: Bruno Guillaume, Guy Perrier, Nicolas Lefebvre.

6.3.1. Crowdsourcing Complex Language Resources

This work [15] presents the results we obtained on a complex annotation task (that of dependency syntax) using a specifically designed Game with a Purpose, ZombiLingo. [0] The design of the game has to deal with the fact that the task is complex and does not directly rely on human intuition. We show that with suitable mechanisms (decomposition of the task, training of the players and regular control of the annotation quality during the game), it is possible to obtain annotations whose quality is significantly higher than that obtainable with a parser, provided that enough players participate. The source code of the game and the resulting annotated corpora (for French) are freely available.

6.3.2. Universal Dependencies

We participated to development of new versions of the French part of the Universal Dependencies project (http://universaldependencies.org/).

The version 1.3 [52] was released in May. In this version, the lemmatization and the morphological annotation were added automatically when possible and with manual verification for ambiguous occurrences.

The version 1.4 [51] was released in November. This version contains a large number of annotation corrections. The Grew software was used to explore, to check consistency and to correct systematically the data. For instance, all copula annotations where checked manually.

7. Partnerships and Cooperations

7.1. Regional Initiatives

7.1.1. Projets Région

7.1.1.1. SLAM

Participants: Maxime Amblard [coordinator], Philippe de Groote, Sylvain Pogodalla.

Schizophrenia is well-known among mental illnesses for the strength of the thought disorders it involves, and for their widespread and spectacular manifestations: from deviant social behavior to delusion, not to speak about affective and sensitive distortions. It aims at exploring a specific manifestation, namely disorders in conversational speech. This is an interdisciplinary research, both empirical and theoretical from several domains, namely psychology, philosophy, linguistic and computer science.

[0] See: http://zombilingo.org/.

The first transcriptions of pathological interviews are analyses. The management chain was implemented for disfluences and POS. Moreover, we have focused on implementing the treatment of lexicography issues and proposed an interface for SDRT-annotations. This year, we have developed a new interaction with the Centre Médical d'Aix-en-Provence in order to collect new interviews. The protocol started at the very end of the year. Moreover we have started the reimplementation of the tool SLAMtk.

The SLAM project was supported by the MSH–Lorraine, USR 3261, the region Grand-Est and the University of Lorraine. We organise the fourth workshop (In)Coherence of Discourse which gather linguists, psychologists and computer scientists in march 2017 : http://discours.loria.fr.

7.1.2. CPER

7.1.2.1. ITL-DI-Oeil

Participant: Maxime Amblard.

Interrelation troubles du langage, discours et processus oculomoteurs

This project is part of another research project about eye-tracking of schizophrenics. It is really close to the SLAM project. One of the main issue is how to collect the data. In order to simplify this clue, the two projects share the same corpus. SLAM is concerned by the transcription of the interviews whereas ITL-DI-Oeil analyses the eye-tracking records.

7.2. National Initiatives

7.2.1. ANR

7.2.1.1. Polymnie: Parsing and synthesis with abstract categorial grammars. From lexicon to discourse

Participants: Maxime Amblard, Philippe de Groote, Aleksandre Maskharashvili, Sylvain Pogodalla [coordinator].

POLYMNIE[0] is a research project funded by the French national research agency (ANR) from September 2012 to February 2016. It relies on the grammatical framework of Abstract Categorial Grammars (ACG). A feature of this formalism is to provide the same mathematical perspective both on the surface forms and on the more abstract forms the latter correspond to. As a consequence:

- ACG allows for the encoding of a large variety of grammatical formalisms such as context-free grammars, Tree Adjoining grammars (TAG), etc.
- ACG defines two languages: an abstract language for the abstract forms, and an object language for the surface forms.

Importantly, the notions of object language and abstract language are relative to each other. If we can naturally see surface forms as strings for instance and abstract forms as the associated syntactic trees, we can also consider to associate this abstract form to a first order logical formula as surface (object) form. This property is central in our project as it offers a unified approach to text analysis and text generation, in particular considering the underlying algorithms and their complexity.

ACG definition uses type-theory and lambda-calculus. From this point of view, they smoothly integrate formal semantics models issuing from Montague's proposal. Theories that extend to the discourse level such as Discourse Representation Theory (DRT) and Dynamic Predicate Logic (DPL) were not initially formulated using lambda-calculus. But such formulations have been proposed. In particular, a formulation based on continuation semantics allows them to be expressed quite naturally in the ACG architecture. Dynamic effects of discourse, in particular those related to anaphora resolution or rhetorical relation inference, have then to be expressed by lexical semantics or computed from the syntactic rules as studied in the Inria Collaborative Research Project (ARC) CAuLD [0].

[0] http://semagramme.loria.fr/doku.php?id=projects:polymnie
[0] https://members.loria.fr/SPogodalla/files/cauld

It has been shown that the discourse structure of texts plays a key role in their understanding. This is the case for both human readers and automatic processing systems. For instance, it can enhance text transformation systems such as the ones performing automatic summarization.

POLYMNIE focuses on studying and implementing the modeling of sentences and discourses in a compositional paradigm that takes into account their dynamics and their structures, both in parsing and in generation. To that end, we rely on the ACG framework. The kind of processing we are interested in relates to the automatic construction of summaries or to text simplification. This has to be considered in the limits of the modeling of the linguistic processes (as opposed to inferential processes for instance) these tasks involve.

Partners:

- Sémagramme people,
- Alpage (Paris 7 university & Inria Paris-Rocquencourt): Laurence Danlos (local coordinator), C. Braud, C. Roze, Éric Villemonte de la Clergerie,
- MELODI (IRIT, CNRS): Stergos Afantenos, Nicholas Asher (local coordinator), Juliette Conrath, Philippe Muller,
- Signes (LaBRI, CNRS): Jérôme Kirman, Richard Moot, Christian Retoré (local coordinator), Sylvain Salvati, Noémie-Fleur Sandillon-Rezer.

The project has been presented during the *journés du numérique de l'ANR* [23]. A demonstration of the ACGtk software has been given during the TALN conference 2016 [22].

7.2.2. DGLFLF (Délégation générale à la langue française et aux langues de France)

7.2.2.1. ZombiLingo

Participants: Bruno Guillaume [coordinator], Nicolas Lefebvre.

The goal of the ZombiLingo project is to develop an online GWAP (Game With A Purpose) to help the construction of linguistic resources. See 6.3.1 for more information.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Events Organisation

8.1.1.1. General Chair, Scientific Chair

MAXIME AMBLARD: LACL 2016 *Logical Aspects of Computational Linguistics 2016*.

8.1.1.2. Member of the Organizing Committees

PHILIPPE DE GROOTE: LACL 2016 *Logical Aspects of Computational Linguistics 2016*.

SYLVAIN POGODALLA: LACL 2016 *Logical Aspects of Computational Linguistics 2016*.

8.1.2. Scientific Events Selection

8.1.2.1. Chair of Conference Program Committees

SYLVAIN POGODALLA: co-chair of FG 2016 *21st Conference on Formal Grammar*[19]; co-chair of LACL 2016 (*Logical Aspects of Computational Linguistics 2016*) [18]

MAXIME AMBLARD: co-chair of LACL 2016 (*Logical Aspects of Computational Linguistics 2016*) [18]

8.1.2.2. Member of the Conference Program Committees

PHILIPPE DE GROOTE: FG 2016, *21st Conference on Formal Grammar*; NLCS'16, *Fourth Workshop on Natural Language and Computer Science*; LACL 2016 *Logical Aspects of Computational Linguistics 2016*.

MAXIME AMBLARD: LACL 2016 *Logical Aspects of Computational Linguistics 2016*; TALN 2016 *Traitement Automatique des Langues 2016*; RECITAL 2016 *Rencontre des Étudiants Chercheurs en Informatique pour le Traitement Automatique des Langues*.

GUY PERRIER: HrTAL2016 *10th International Conference on Natural Language Processing*.

8.1.2.3. Reviewer

PHILIPPE DE GROOTE: FG 2016, *21st Conference on Formal Grammar*; NLCS'16, *Fourth Workshop on Natural Language and Computer Science*; LACL 2016 *Logical Aspects of Computational Linguistics 2016*.

SYLVAIN POGODALLA: NISM 2016 *New Ideas in Semantics and Modelisation*; Cognitive Structures: Linguistic, Philosophical and Psychological Perspectives; FG 2016 *21st Conference on Formal Grammar*; LACL 2016 *Logical Aspects of Computational Linguistics 2016*.

MAXIME AMBLARD: LACL 2016 *Logical Aspects of Computational Linguistics 2016*; TALN 2016 *Traitement Automatique des Langues 2016*; RECITAL 2016 *Rencontre des Étudiants Chercheurs en Informatique pour le Traitement Automatique des Langues*.

GUY PERRIER: HrTAL2016 *10th International Conference on Natural Language Processing*; LACL 2016 *Logical Aspects of Computational Linguistics 2016*.

8.1.3. Journal

8.1.3.1. Member of the Editorial Boards

PHILIPPE DE GROOTE: area editor of the *FoLLI-LNCS series*; associate editor of *Higher-Order and Symbolic Computation*; member of the editorial board of *Cahiers du Centre de Logique*.

SYLVAIN POGODALLA: Member of the editorial board of the journal *Traitement Automatique des Langues*, in charge of the *Résumés de thèses* section.

MAXIME AMBLARD: Member of the editorial board of the journal *Traitement Automatique des Langues*, in charge of the final editing process

8.1.3.2. Reviewer - Reviewing Activities

PHILIPPE DE GROOTE: *Journal of Logic, Language and Information*; *Journal of Applied Logic*.

SYLVAIN POGODALLA: *Journal of Language Modelling*; *Traitement Automatique des Langues*.

MAXIME AMBLARD: *Traitement Automatique des Langues*.

8.1.4. Invited Talks

MAXIME AMBLARD: *Sémantique : modélisation formelle et interprétation de données empiriques*, ATILF, Nancy; *L'informaticien face au traitement du langage : que peut-on faire et que croit-on que nous faisons ?*, at the occasion of *Images du savoir pratique : les figures de l'informaticien et du médecin dans les récits de fiction populaire contemporains*, IRIST, Strasbourg.

8.1.5. Leadership within the Scientific Community

PHILIPPE DE GROOTE: vice president of SIGMOL, *Association for Mathematics of Language, a Special Interest Group of the Association for Computational Linguistics*; member of the LACL steering committee.

BRUNO GUILLAUME: nominated as a Management Committee Substitute of the COST Action CA16105 "European Network for Combining Language Learning with Crowdsourcing Techniques" (http://www.cost.eu/COST_Actions/ca/CA16105)

SYLVAIN POGODALLA: member of the LACL steering committee; member of the Formal Grammar standing committee.

8.1.6. Scientific Expertise

PHILIPPE DE GROOTE: expert for the FNRS, *Fond National de la Recherche Scientifique*, Belgium; expert for the *National Science Center*, Poland.

SYLVAIN POGODALLA: expert for the Research Executive Agency (REA) of the EU.

MAXIME AMBLARD: member of the PhD award of ATALA

8.1.7. Research Administration

PHILIPPE DE GROOTE: member of the *bureau du comité des projets d'Inria-Nancy*.

BRUNO GUILLAUME:

- Head of the Loria department NLPKD (Natural Language Processing and Kownledge Discovery)
- Animator of the CPER 2015-2020 project *Langues, Connaissances et Humanités Numériques'* (Languages, Knowledge and Digital Humanities) in which ten laboratories of the *Université de Lorraine* are implied.
- Elected member of the *Pôle scientifique AM2I* of the Université de Lorraine.
- Member of the Comipers (Inria committee for PhD and Post-doctoral selection).

MAXIME AMBLARD:

- member of *conseil scientifique de l'Université de Lorraine*.
- member of *conseil de laboratoire du Loria*
- member of *conseil de gestion de la Maison des sciences de l'homme, MSH-Lorraine*
- head of the master (M2) in Natural Language Processing.
- in charge of the proposal of a new master in NLP.

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

Licence: Maxime Amblard, Formalismes de représentation et raisonnement, 25h, L3, Université de Lorraine, France

Licence: Maxime Amblard, C2i, 20h, L1, Université de Lorraine, France

Licence: Jirka Maršík, Ingénierie linguistique, 25h, L3, Université de Lorraine, France

Master: Maxime Amblard, Formalisms : from Syntax to Discourse, 50h, M2, Univ. Lorraine, France

Master: Maxime Amblard, Remise à niveau TAL, 6h, M2, Université de Lorraine, France

Master: Maxime Amblard, Programming for NLP, 44h, M1, Université de Lorraine, France

Master: Philippe de Groote, Formal logic, 35h, M2, Université de Lorraine, France.

Master: Philippe de Groote, Computational structures and logics for natural language modelling, 18h, M2, Université Paris Diderot, France.

Master : Bruno Guillaume, NLP Toolchain and Linguistic Resources, 15h, M2, Université de Lorraine, France.

Master: Jirka Maršík, IA fondamentale : représentation des connaissances et fouille de données, 11h30, M1, Université de Lorraine, France

Master: Jirka Maršík, Communication scientifique, 15h30, M1, Université de Lorraine, France

Master: Jirka Maršík, Cognitive Aspect of Computational Linguistic, 15h, M2, Université de Lorraine, France

Master: Jirka Maršík, Aspects cognitives de la linguistique computationnelle, 16h30, M2, Université de Lorraine, France

Master: Jirka Maršík, Remise à niveau TAL, 10h, M2, Université de Lorraine, France

Master : Sylvain Pogodalla, Formal Languages, 24h, M2, Université de Lorraine, France.

8.2.2. Supervision

HdR: Maxime Amblard, Sémantique et discours, de la modélisation à l'interprétation, Université de Lorraine, November 28th, 2016, Philippe de Groote.

PhD: Jirka Maršík, Effects and Handlers in Natural Language, Université de Lorraine, December 9th, 2016, Philippe de Groote and Maxime Amblard.

PhD: Aleksandre Maskharashvili, Discourse Modeling with Abstract Categorial Grammars, Université de Lorraine, December 1st, 2016, Philippe de Groote and Sylvain Pogodalla.

PhD in progress: Clément Beysson, Quantificateurs généralisés dynamiques pour l'analyse discursive, since september 2015, Philippe de Groote and Bruno Guillaume.

8.2.3. Juries

PHILIPPE DE GROOTE was member of the jury of the HdR of Maxime Amblard, *Sémantique et discours, de la modélisation à l'interprétation* [6], November 28th, 2016, Université de Lorraine.

PHILIPPE DE GROOTE was member of the jury of the PhD thesis of Aleksandre Maskharashvili, *Discourse Modeling with Abstract Categorial Grammars* [8], December 1st, 2016, Université de Lorraine.

PHILIPPE DE GROOTE was member of the jury of the PhD thesis of Jirka Maršík, *Effects and Handlers in Natural Language* [7], Université de Lorraine, December 9th, 2016, Université de Lorraine.

SYLVAIN POGODALLA was member of the jury of the PhD thesis of Aleksandre Maskharashvili, *Discourse Modeling with Abstract Categorial Grammars* [8], December 1st, 2016, Université de Lorraine.

MAXIME AMBLARD was member of the jury of the PhD thesis of Jirka Maršík, *Effects and Handlers in Natural Language* [7], Université de Lorraine, December 9th, 2016, Université de Lorraine.

GUY PERRIER was member of the jury of the PhD thesis of Bikash Gyawali *Surface Realisation from Knowledge Bases*, January 20, 2016, Université de Lorraine.

8.3. Popularization

- Maxime Amblard is scientific vice head of the editorial board of interstice)i(, a french magazine popularizing computer sciences. He is the head of the rubric *informatique —ou presque— dans les films*.
- Maxime Amblard was scientific expert for the exhibition *Homo Numericus*.
- Bruno Guillaume was invited twice to present and lead an open discussion about Citizen Science: *Séminaire ESPÉ DANE : la pépinière 4.0*, in January, and *Séminaire ESPÉ DANE : la pépinière 4.1*, in October.
- Bruno Guillaume was invited in July to a panel discussion about Citizen Science, *Les rendez-vous de Science&You*.

9. Bibliography

Major publications by the team in recent years

[1] G. BONFANTE, B. GUILLAUME, M. MOREY, G. PERRIER.*Modular Graph Rewriting to Compute Semantics*, in "9th International Conference on Computational Semantics - IWCS 2011", Oxford, Royaume-Uni, J. BOS, S. PULMAN (editors), January 2011, p. 65–74, http://hal.inria.fr/inria-00579244/en/.

[2] B. GUILLAUME, G. PERRIER.*Interaction Grammars*, in "Research on Language & Computation", 2009, vol. 7, p. 171–208.

[3] P. DE GROOTE.*Towards abstract categorial grammars*, in "Association for Computational Linguistics, 39th Annual Meeting and 10th Conference of the European Chapter", Toulouse, France, none, July 2001, p. 148-155, Colloque avec actes et comité de lecture. internationale, http://hal.inria.fr/inria-00100529/en.

[4] P. DE GROOTE, S. POGODALLA.*On the expressive power of abstract categorial grammars: Representing context-free formalisms*, in "Journal of Logic, Language and Information", 2004, vol. 13, n^{o} 4, p. 421–438.

[5] P. DE GROOTE.*Towards a Montagovian Account of Dynamics*, in "16th Semantics and Linguistic Theory conference - SALT2006", Tokyo, Japan, M. GIBSON, J. HOWELL (editors), 2006, http://elanguage.net/journals/index.php/salt/article/view/16.1.

Publications of the year

Doctoral Dissertations and Habilitation Theses

[6] M. AMBLARD.*Semantics and Discourse: from modelling to interpretation*, Université de Lorraine (Nancy), November 2016, Habilitation à diriger des recherches, https://hal.inria.fr/tel-01415967.

[7] J. MARŠÍK.*Effects and Handlers in Natural Language*, Université de Lorraine, December 2016, https://hal.inria.fr/tel-01417467.

[8] A. MASKHARASHVILI.*Discourse Modeling with Abstract Categorial Grammars*, University of Lorraine ; Inria Nancy - Grand Est (Villers-lès-Nancy, France), December 2016, https://hal.inria.fr/tel-01412765.

Articles in International Peer-Reviewed Journal

[9] M. AMBLARD.*Pour un TAL responsable*, in "Traitement Automatique des Langues", 2016, vol. 57, n^{o} 2, p. 21 - 45, https://hal.inria.fr/hal-01414145.

[10] M. AMBLARD, A. BOUMAZA.*Human Robots, Are You Real Then?*, in "Iride", 2016, vol. XXIX, n^{o} 2, p. 287-298 [*DOI :* 10.1414/84251], https://hal.inria.fr/hal-01391754.

[11] S. QIAN, P. DE GROOTE, M. AMBLARD.*Modal Subordination in Type Theoretic Dynamic Logic*, in "Linguistic Issues in Language Technology", August 2016, vol. 14, 54, https://hal.inria.fr/hal-01370557.

Invited Conferences

[12] M. AMBLARD.*L'informaticien face au traitement du langage : que peut-on faire et que croit-on que nous faisons ?*, in "Séminaire 2015/2016 « Images du savoir pratique : les figures de l'informaticien et du médecin dans les récits de fiction populaire contemporains", Strasbourg, France, February 2016, https://hal.inria.fr/hal-01280932.

International Conferences with Proceedings

[13] L. DANLOS, A. MASKHARASHVILI, S. POGODALLA.*Interfacing Sentential and Discourse TAG-based Grammars*, in "The 12th International Workshop on Tree Adjoining Grammars and Related Formalisms

(TAG+12)", Düsseldorf, Germany, Proceedings of the 12th International Workshop on Tree Adjoining Grammars and Related Formalisms (TAG+12), June 2016, https://hal.inria.fr/hal-01328697.

[14] P. DE GROOTE.*Lambek Categorial Grammars as Abstract Categorial Grammars*, in "LENLS 13", Tokyo, Japan, Logic and Engineering of Natural Language Semantics 13, October 2016, https://hal.inria.fr/hal-01412795.

[15] B. GUILLAUME, K. FORT, N. LEFÈBVRE.*Crowdsourcing Complex Language Resources: Playing to Annotate Dependency Syntax*, in "International Conference on Computational Linguistics (COLING)", Osaka, Japan, Proceedings of the 26th International Conference on Computational Linguistics (COLING), December 2016, https://hal.inria.fr/hal-01378980.

[16] J. MARŠÍK, M. AMBLARD.*Introducing a Calculus of Effects and Handlers for Natural Language Semantics*, in "Formal Grammar 2016", Bozen-Bolzano, Italy, A. FORET, G. MORRILL, R. MUSKENS, R. OSSWALD, S. POGODALLA (editors), Lecture Notes in Computer Science,, Springer Berlin Heidelberg, August 2016, vol. 9804, p. 257–272 [*DOI :* 10.1007/978-3-662-53042-9], https://hal.inria.fr/hal-01332762.

Scientific Books (or Scientific Book chapters)

[17] L. KALLMEYER, R. OSSWALD, S. POGODALLA.*For-Adverbials and Aspectual Interpretation: An LTAG Analysis Using Hybrid Logic and Frame Semantics*, in "Empirical Issues in Syntax and Semantics 11", C. PIÑÓN (editor), Empirical Issues in Syntax and Semantics, 2016, vol. 11, https://hal.inria.fr/hal-01417847.

Books or Proceedings Editing

[18] M. AMBLARD, P. DE GROOTE, S. POGODALLA, C. RETORÉ (editors). *Logical Aspects of Computational Linguistics. Celebrating 20 Years of LACL (1996–2016): 9th International Conference, LACL 2016, Nancy, France, December 5-7, 2016, Proceedings*, Lecture Notes in Computer Science, Springer Berlin Heidelberg, Nancy, France, 2016, vol. 10054 [*DOI :* 10.1007/978-3-662-53826-5], https://hal.inria.fr/hal-01403271.

[19] A. FORET, G. MORRILL, R. MUSKENS, R. OSSWALD, S. POGODALLA (editors). *Formal Grammar: 20th and 21st International Conferences, FG 2015, Barcelona, Spain, August 2015, Revised Selected Papers. FG 2016, Bozen, Italy, August 2016, Proceedings*, Lecture Notes in Computer Science, Springer Berlin Heidelberg, Italy, 2016, vol. 9804 [*DOI :* 10.1007/978-3-662-53042-9], https://hal.inria.fr/hal-01360105.

Scientific Popularization

[20] M. AMBLARD.*Regard sur « À quoi rêvent les algorithmes »*, in "Interstices", January 2016, https://hal.inria.fr/hal-01280938.

Other Publications

[21] L. KALLMEYER, R. OSSWALD, S. POGODALLA.*Quantification in Frame Semantics with Binders and Nominals of Hybrid Logic*, December 2016, Submitted, https://hal.inria.fr/hal-01417853.

[22] S. POGODALLA.*ACGTK: un outil de développement et de test pour les grammaires catégorielles abstraites*, Actes de la 23ème Conférence sur le Traitement Automatique des Langues Naturelles, 31ème Journées d'Études sur la Parole, 18ème Rencontre des Étudiants Chercheurs en Informatique pour le Traitement Automatique des Langues, July 2016, JEP-TALN-RECITAL 2016, Poster - Démonstration aux 23ème Conférence sur le Traitement Automatique des Langues Naturelles JEP-TALN-RECITAL 2016, Paris, France, https://hal.inria.fr/hal-01328702.

[23] S. POGODALLA.*Parsing and Generation with Abstract Categorial Grammars : From Lexicon to Discourse*, November 2016, Les rencontres du numérique de l'ANR, Poster, https://hal.inria.fr/hal-01417895.

References in notes

[24] P. BLACKBURN, J. V. BENTHEM, F. WOLTER (editors). *Handbook of Modal Logic*, Studies in Logic and Practical Reasoning, Elsevier, 2007, vol. 3.

[25] T. GAMERSCHLAG, D. GERLAND, R. OSSWALD, W. PETERSEN (editors). *Frames and Concept Types*, Studies in Linguistics and Philosophy, Springer International Publishing, 2014, vol. 94, http://dx.doi.org/10.1007/978-3-319-01541-5.

[26] C. ARECES, B. TEN CATE.*Hybrid logics*, in "Handbook of Modal Logic", P. BLACKBURN, J. V. BENTHEM, F. WOLTER (editors), Studies in Logic and Practical Reasoning, Elsevier, 2007, vol. 3, chap. 14, p. 821–868, http://dx.doi.org/10.1016/S1570-2464(07)80017-6.

[27] Y. BAR-HILLEL.*Out of the pragmatic wastebasket*, in "Linguistic Inquiry", 1971, vol. 2, n^{o} 3, p. 401–407.

[28] C. BARKER.*Continuations and the Nature of Quantification*, in "Natural Language Semantics", 2002, vol. 10, n^{o} 3, p. 211–242.

[29] C. BARKER.*Continuations in Natural Language*, in "Proceedings of the Fourth ACM SIGPLAN Continuations Workshop (CW'04)", 2004.

[30] L. BARSALOU.*Frames, concepts, and conceptual fields*, in "Frames, fields, and contrasts: New essays in semantic and lexical organization", Hillsdale, A. LEHRER, E. F. KITTEY (editors), Lawrence Erlbaum Associates, 1992, p. 21–74.

[31] N. CHOMSKY.*Three models for the description of language*, in "Information Theory, IRE Transactions on", 1956, vol. 2, n^{o} 3, p. 113–124.

[32] A. CHURCH.*A formulation of the simple theory of types*, in "The journal of symbolic logic", 1940, vol. 5, n^{o} 2, p. 56–68.

[33] L. DANLOS.*D-STAG: a discourse analysis formalism based on synchronous TAGs*, in "TAL", 2009, vol. 50, n^{o} 1, p. 111–143.

[34] L. DANLOS.*G-TAG : un formalisme lexicalisé pour la génération de textes inspiré de TAG*, in "Traitement Automatique des Langues", 1998, vol. 39, n^{o} 2, 28 p.

[35] M. FELLEISEN, D. P. FRIEDMAN, E. KOHLBECKER, B. DUBA.*A syntactic theory of sequential control*, in "Theor. Comput. Sci.", June 1987, vol. 52, p. 205–237, http://dx.doi.org/10.1016/0304-3975(87)90109-5.

[36] M. FELLEISEN, R. HIEB.*The revised report on the syntactic theories of sequential control and state*, in "Theoretical Computer Science", 1992, vol. 103, n^{o} 2, p. 235 - 271 [*DOI :* 10.1016/0304-3975(92)90014-7], http://www.sciencedirect.com/science/article/pii/0304397592900147.

[37] C. J. FILLMORE.*Frame Semantics*, in "Linguistics in the Morning Calm", Seoul, T. L. S. OF KOREA (editor), Hanshin Publishing Co., 1982, p. 111–137.

[38] K. FORBES, E. MILTSAKAKI, R. PRASAD, A. SARKAR, A. K. JOSHI, B. L. WEBBER.*D-LTAG System: Discourse Parsing with a Lexicalized Tree-Adjoining Grammar*, in "Journal of Logic, Language and Information", 2003, vol. 12, n^{o} 3, p. 261–279.

[39] D. GALLIN.*Intensional and higher-order modal logic: with applications to Montague semantics*, North-Holland mathematics studies, North-Holland, 1975, http://books.google.fr/books?id=jkiNo5Rok7cC.

[40] J. GROENENDIJK, M. STOKHOF.*Dynamic predicate logic*, in "Linguistics and philosophy", 1991, vol. 14, n^{o} 1, p. 39–100.

[41] H. KAMP, U. REYLE.*From discourse to logic: Introduction to modeltheoretic semantics of natural language, formal logic and discourse representation theory*, Kluwer Academic Dordrecht, The Netherlands, 1993, vol. 42.

[42] M. KANAZAWA, S. SALVATI.*Generating Control Languages with Abstract Categorial Grammars*, in "Proceedings of the 12th conference on Formal Grammar", 2007.

[43] J. LAMBEK.*The mathematics of sentence structure*, in "The American Mathematical Monthly", 1958, vol. 65, n^{o} 3, p. 154–170.

[44] S. LÖBNER.*Sub-compositionality*, in "The Oxford Handbook of Compositionality", M. WERNING, W. HINZEN, E. MACHERY (editors), Oxford Handbooks in Linguistics, Oxford University Press, 2012, chap. 10, p. 220-241.

[45] S. LÖBNER.*Evidence for frames from human language*, in "Frames and Concept Types", Dordrecht, T. GAMERSCHLAG, D. GERLAND, R. OSSWALD, W. PETERSEN (editors), Studies in Linguistics and Philosophy, Springer, 2014, vol. 94, n^{o} 94, p. 23–67, http://dx.doi.org/10.1007/978-3-319-01541-5_2.

[46] R. MONTAGUE.*English as a formal language*, in "Linguaggi nella societae nella tecnica", 1970, p. 189–224.

[47] R. MONTAGUE.*Universal grammar*, in "Theoria", 1970, vol. 36, n^{o} 3, p. 373–398.

[48] R. MONTAGUE.*The Proper Treatment of Quantification in Ordinary English*, in "Formal Semantics", 1973, p. 221–242.

[49] M. MOORTGAT.*Categorial type logics*, in "Handbook of logic and language", 1997, p. 93–177.

[50] C. MORRIS.*Foundations of the Theory of Signs*, University of Chicago Press, 1938, vol. 1.

[51] J. NIVRE, Ž. AGIĆ, L. AHRENBERG, M. J. ARANZABE, M. ASAHARA, A. ATUTXA, M. BALLESTEROS, J. BAUER, K. BENGOETXEA, Y. BERZAK, R. A. BHAT, E. BICK, C. BÖRSTELL, C. BOSCO, G. BOUMA, S. BOWMAN, G. CEBIROĞLU ERYIĞIT, G. G. A. CELANO, F. CHALUB, Ç. ÇÖLTEKIN, M. CONNOR, E. DAVIDSON, M.-C. DE MARNEFFE, A. DIAZ DE ILARRAZA, K. DOBROVOLJC, T. DOZAT, K. DROGANOVA, P. DWIVEDI, M. ELI, T. ERJAVEC, R. FARKAS, J. FOSTER, C. FREITAS, K. GAJDOŠOVÁ, D. GALBRAITH, M. GARCIA, M. GÄRDENFORS, S. GARZA, F. GINTER, I. GOENAGA, K. GOJENOLA,

M. Gökirmak, Y. Goldberg, X. Gómez Guinovart, B. Gonzáles Saavedra, M. Grioni, N. Grūzītis, B. Guillaume, J. Hajič, L. Hà Mỹ, D. Haug, B. Hladká, R. Ion, E. Irimia, A. Johannsen, F. Jørgensen, H. Kaşikara, H. Kanayama, J. Kanerva, B. Katz, J. Kenney, N. Kotsyba, S. Krek, V. Laippala, L. Lam, P. Lê Hồng, A. Lenci, N. Ljubešić, O. Lyashevskaya, T. Lynn, A. Makazhanov, C. Manning, C. Mărănduc, D. Mareček, H. Martínez Alonso, A. Martins, J. Mašek, Y. Matsumoto, R. McDonald, A. Missilä, V. Mititelu, Y. Miyao, S. Montemagni, K. S. Mori, S. Mori, B. Moskalevskyi, K. Muischnek, N. Mustafina, K. Müürisep, L. Nguyễn Thị, H. Nguyễn Thị Minh, V. Nikolaev, H. Nurmi, P. Osenova, R. Östling, L. Øvrelid, V. Paiva, E. Pascual, M. Passarotti, C.-A. Perez, S. Petrov, J. Piitulainen, B. Plank, M. Popel, L. Pretkalniņa, P. Prokopidis, T. Puolakainen, S. Pyysalo, A. Rademaker, L. Ramasamy, L. Real, L. Rituma, R. Rosa, S. Saleh, B. Saulīte, S. Schuster, W. Seeker, M. Seraji, L. Shakurova, M. Shen, N. Silveira, M. Simi, R. Simionescu, K. Simkó, M. Šimková, K. Simov, A. Smith, C. Spadine, A. Suhr, U. Sulubacak, Z. Szántó, T. Tanaka, R. Tsarfaty, F. Tyers, S. Uematsu, L. Uria, G. van Noord, V. Varga, V. Vincze, L. Wallin, J. X. Wang, J. N. Washington, M. Wirén, Z. Žabokrtský, A. Zeldes, D. Zeman, H. Zhu.*Universal Dependencies 1.4*, 2016, LINDAT/CLARIN digital library at the Institute of Formal and Applied Linguistics, Charles University in Prague, http://hdl.handle.net/11234/1-1827.

[52] J. Nivre, Ž. Agić, L. Ahrenberg, M. J. Aranzabe, M. Asahara, A. Atutxa, M. Ballesteros, J. Bauer, K. Bengoetxea, Y. Berzak, R. A. Bhat, C. Bosco, G. Bouma, S. Bowman, G. Cebiroğlu Eryiğit, G. G. A. Celano, Ç. Çöltekin, M. Connor, M.-C. de Marneffe, A. Diaz de Ilarraza, K. Dobrovoljc, T. Dozat, K. Droganova, T. Erjavec, R. Farkas, J. Foster, D. Galbraith, S. Garza, F. Ginter, I. Goenaga, K. Gojenola, M. Gokirmak, Y. Goldberg, X. Gómez Guinovart, B. Gonzáles Saavedra, N. Grūzītis, B. Guillaume, J. Hajič, D. Haug, B. Hladká, R. Ion, E. Irimia, A. Johannsen, H. Kaşikara, H. Kanayama, J. Kanerva, B. Katz, J. Kenney, S. Krek, V. Laippala, L. Lam, A. Lenci, N. Ljubešić, O. Lyashevskaya, T. Lynn, A. Makazhanov, C. Manning, C. Mărănduc, D. Mareček, H. Martínez Alonso, J. Mašek, Y. Matsumoto, R. McDonald, A. Missilä, V. Mititelu, Y. Miyao, S. Montemagni, K. S. Mori, S. Mori, K. Muischnek, N. Mustafina, K. Müürisep, V. Nikolaev, H. Nurmi, P. Osenova, L. Øvrelid, E. Pascual, M. Passarotti, C.-A. Perez, S. Petrov, J. Piitulainen, B. Plank, M. Popel, L. Pretkalniņa, P. Prokopidis, T. Puolakainen, S. Pyysalo, L. Ramasamy, L. Rituma, R. Rosa, S. Saleh, B. Saulīte, S. Schuster, W. Seeker, M. Seraji, L. Shakurova, M. Shen, N. Silveira, M. Simi, R. Simionescu, K. Simkó, K. Simov, A. Smith, C. Spadine, A. Suhr, U. Sulubacak, Z. Szántó, T. Tanaka, R. Tsarfaty, F. Tyers, S. Uematsu, L. Uria, G. van Noord, V. Varga, V. Vincze, J. X. Wang, J. N. Washington, Z. Žabokrtský, D. Zeman, H. Zhu.*Universal Dependencies 1.3*, 2016, LINDAT/CLARIN digital library at the Institute of Formal and Applied Linguistics, Charles University in Prague, http://hdl.handle.net/11234/1-1699.

[53] G. Perrier.*A French Interaction Grammar*, in "International Conference on Recent Advances in Natural Language Processing - RANLP 2007", Borovets, Bulgarie, G. Angelova, K. Bontcheva, R. Mitkov, N. Nicolov, K. Simov (editors), INCOMA Ltd, Shoumen, Bulgaria, 2007, p. 463-467, http://hal.inria.fr/inria-00184108/en/.

[54] S. Pogodalla.*Computing Semantic Representation: Towards ACG Abstract Terms as Derivation Trees*, in "Seventh International Workshop on Tree Adjoining Grammar and Related Formalisms - TAG+7", Vancouver, BC, Canada, 2004, p. 64-71, Colloque avec actes et comité de lecture. Internationale, https://hal.inria.fr/inria-00107768.

[55] C. Retoré, S. Salvati.*A Faithful Representation of Non-Associative Lambek Grammars in Abstract Categorial Grammars*, in "Journal of Logic Language and Information", April 2010, vol. 19, n^{o} 2, p. 185–200, http://hal.inria.fr/inria-00409557/en/.

[56] J. ROGERS.*A model-theoretic framework for theories of syntax*, in "Proceedings of the 34th annual meeting on Association for Computational Linguistics", Association for Computational Linguistics, 1996, p. 10–16.

[57] C.-C. SHAN.*Delimited continuations in natural language: quantification and polarity sensitivity*, in "CoRR", 2004, vol. cs.CL/0404006.

[58] C. STRACHEY, C. P. WADSWORTH.*Continuations: A Mathematical Semantics for Handling Full Jumps*, in "Higher-Order and Symbolic Computation", 1974, vol. 13, p. 135–152.

[59] P. DE GROOTE.*Tree-Adjoining Grammars as Abstract Categorial Grammars*, in "TAG+6, Proceedings of the sixth International Workshop on Tree Adjoining Grammars and Related Frameworks", Università di Venezia, 2002, p. 145–150.

[60] P. DE GROOTE, S. POGODALLA.*m-linear context-free rewriting systems as abstract categorial grammars*, in "oceedings of Mathematics of Language - MOL-8", 2003.

[61] J. VAN BENTHEM.*Essays in logical semantics*, Reidel, 1986, n^{o} 29.

Project-Team SPHINX

Heterogeneous Systems: Inverse Problems, Control and Stabilization, Simulation

IN COLLABORATION WITH: Institut Elie Cartan de Lorraine (IECL)

IN PARTNERSHIP WITH:
CNRS

Université de Lorraine

RESEARCH CENTER
Nancy - Grand Est

THEME
Optimization and control of dynamic systems

Table of contents

Project-Team SPHINX

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

Keywords:

Computer Science and Digital Science:

6. - Modeling, simulation and control
6.1. - Mathematical Modeling
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
6.2.7. - High performance computing
6.4. - Automatic control
6.4.1. - Deterministic control
6.4.3. - Observability and Controlability
6.4.4. - Stability and Stabilization

Other Research Topics and Application Domains:

2. - Health
2.6. - Biological and medical imaging
5. - Industry of the future
5.6. - Robotic systems
9. - Society and Knowledge
9.4. - Sciences
9.4.2. - Mathematics
9.4.3. - Physics
9.4.4. - Chemistry

1. Members

Research Scientists

Takéo Takahashi [Team leader, Inria, Researcher, HDR]
Karim Ramdani [Inria, Senior Researcher, HDR]
Jean-Claude Vivalda [Inria, Senior Researcher, HDR]

Faculty Members

Xavier Antoine [Univ. Lorraine, Professor, HDR]
Thomas Chambrion [Univ. Lorraine, Associate Professor, HDR]
David Dos Santos Ferreira [Univ. Lorraine, Professor, HDR]
Julien Lequeurre [Univ. Lorraine, Associate Professor]
Alexandre Munnier [Univ. Lorraine, Associate Professor]
Jean-François Scheid [Univ. Lorraine, Associate Professor, HDR]
Julie Valein [Univ. Lorraine, Associate Professor]

PhD Students

Boris Caudron [Thales]
Chi-Ting Wu [Univ. Lorraine, until Sep 2016]

Post-Doctoral Fellows
Mohamed El Bouajaji [Univ. Lorraine, until Aug 2016]
Qinglin Tang [Rouen University, until Aug 2016]

Administrative Assistant
Céline Simon [Inria]

Others
Nicolas Ratto [Inria, Internship, from Mar 2016 until Aug 2016]
Arnab Roy [TIFR Bangalore, PhD Student, from Oct 2016 until Nov 2016]

2. Overall Objectives

2.1. Overall Objectives

In this project, we investigate theoretical and numerical mathematical issues concerning heterogeneous physical systems. The heterogeneities we consider result from the fact that the studied systems involve subsystems of different physical nature. In this wide class of problems, we study two types of systems: **fluid-structure interaction systems (FSIS)** and **complex wave systems (CWS)**. In both situations, one has to develop specific methods to take into account the coupling between the subsystems.

(FSIS) Fluid-structure interaction systems appear in many applications: medicine (motion of the blood in veins and arteries), biology (animal locomotion in a fluid, such as swimming fish or flapping birds but also locomotion of microorganisms, such as amoebas), civil engineering (design of bridges or any structure exposed to the wind or the flow of a river), naval architecture (design of boats and submarines, seeking of new propulsion systems for underwater vehicles by imitating the locomotion of aquatic animals). The FSIS can be studied by modeling their motions through Partial Differential Equations (PDE) and/or Ordinary Differential Equations (ODE), as is classical in fluid mechanics or in solid mechanics. This leads to the study of difficult nonlinear free boundary problems which constitute a rich and active domain of research over the last decades.

(CWS) Complex wave systems are involved in a large number of applications in several areas of science and engineering: medicine (breast cancer detection, kidney stones destruction, osteoporosis diagnosis, etc.), telecommunications (in urban or submarine environments, optical fibers, etc.), aeronautics (targets detection, aircraft noise reduction, etc.) and, in the longer term, quantum supercomputers. **For direct problems**, most theoretical issues are now widely understood. However, substantial efforts remain to be undertaken concerning the simulation of wave propagation in complex media. Such situations include heterogeneous media with strong local variations of the physical properties (high frequency scattering, multiple scattering media) or quantum fluids (Bose-Einstein condensates). In the first case for instance, the numerical simulation of such direct problems is a hard task, as it generally requires solving ill-conditioned possibly indefinite large size problems, following from space or space-time discretizations of linear or nonlinear evolution PDE set on unbounded domains. **For inverse problems**, many questions are open at both the theoretical (identifiability, stability and robustness, etc.) and practical (reconstruction methods, approximation and convergence analysis, numerical algorithms, etc.) levels.

3. Research Program

3.1. Control and stabilization of heterogeneous systems

Fluid-Structure Interaction Systems (FSIS) are present in many physical problems and applications. Their study involves to solve several challenging mathematical problems:

- **Nonlinearity:** One has to deal with a system of nonlinear PDE such as the Navier-Stokes or the Euler systems;

- **Coupling:** The corresponding equations couple two systems of different types and the methods associated with each system need to be suitably combined to solve successfully the full problem;
- **Coordinates:** The equations for the structure are classically written with Lagrangian coordinates whereas the equations for the fluid are written with Eulerian coordinates;
- **Free boundary:** The fluid domain is moving and its motion depends on the motion of the structure. The fluid domain is thus an unknown of the problem and one has to solve a free boundary problem.

In order to control such FSIS systems, one has first to analyze the corresponding system of PDE. The oldest works on FSIS go back to the pioneering contributions of Thomson, Tait and Kirchhoff in the 19th century and Lamb in the 20th century, who considered simplified models (potential fluid or Stokes system). The first mathematical studies in the case of a viscous incompressible fluid modeled by the Navier-Stokes system and a rigid body whose dynamics is modeled by Newton's laws appeared much later [108], [100], [79], and almost all mathematical results on such FSIS have been obtained in the last twenty years.

The most studied issue concerns the well-posedness of the problem modeling a **rigid body moving into a viscous incompressible fluid**. If the fluid fills the **unbounded domain** surrounding the structure, the free boundary difficulty can be overcome by using a simple change of variables that makes the rigid body fixed. One can then use classical tools for the Navier-Stokes system and obtain the existence of weak solutions (see, for instance, [67], [68], [101]) or strong solutions for the case of a ball [105]. When the rigid body is not a ball, the additional terms due to the change of variables modify the nature of the system and only partial results are available for strong solutions [69], [54], [102]. When the fluid-solid system is confined in a **bounded domain**, the above strategy fails. Several papers have developed interesting strategies in order to obtain the existence of solutions. Since the coupling is strong, it is natural to consider a variational formulation for both the fluid and the structure equations (see [57]). One can then solve the FSIS by considering the Navier-Stokes system with a penalization term taking into account the structure ([51], [99], [63]) or using a time discretization in order to fix the rigid body during some time interval ([73]). Using an appropriate change of variables has also been used (see [72], [104]), but of course, its construction is more complex than in the case where the FSIS fills the whole space. Most of the above results only hold up to a possible contact between two structures or between a structure and the exterior boundary. If the considered configuration excludes contacts, some authors also investigated the long-time behavior of this system and the existence of time periodic solutions [107], [89], [70].

Many other FSIS have been studied as well. Let us mention, for instance, **rigid bodies immersed in an incompressible perfect fluid** ([91], [76], [71]), **in a viscous compressible fluid** ([56], [44], [62], [45]), in a **viscous multipolar fluid** or in an **incompressible non-Newtonian fluid** ([64]). The case of **deformable structures** has also been considered, either for a fluid inside a moving structure (e.g. blood motion in arteries) or for a moving deformable structure immersed in a fluid (e.g. fish locomotion). Several models for the dynamics of the deformable structure exist: one can use the plate equations or the elasticity equations. The obtained coupled FSIS is a complex system and the study of its well-posedness raises several difficulties. The main one comes from the fact that we gather two systems of different nature, as the linearized problem couples a parabolic system with a hyperbolic one. Theoretical studies have been performed for approximations of the complete system, using two strategies: adding a regularizing term in the linear elasticity equations (see [49], [44], [82]) or approximate the equations of linear elasticity by a system of finite dimension (see [58], [47]). For strong solutions, the coupling between hyperbolic-parabolic systems leads to seek solutions with high regularity. The only known results [52], [53] in this direction concern local (in time) existence of regular solutions, under strong assumptions on the regularity of the initial data. Such assumptions are not very satisfactory but seem inherent in this coupling between two systems of different natures. Another option is to consider approximate models, but so far, the available approximations are not obtained from a physical model and deriving a more realistic model is a difficult task.

In some particular important physical situations, one can also consider a simplified model. For instance, in order to study self-propelled motions of structures in a fluid, like fish locomotion, one can assume that the **deformation of the structure is prescribed and known**, whereas its displacement remains unknown ([97]).

Although simplified, this model already contains many difficulties and permits to start the mathematical study of a challenging problem: understanding the locomotion mechanism of aquatic animals.

Using the above results and the corresponding tools, we aim to consider control or stabilization problems for FSIS. Some control problems have already been considered: using an interior control in the fluid region, it is possible to control locally the velocity of the fluid together with the velocity and the position of the rigid body (see [77], [46]). The strategy of control is similar to the classical method for a fluid (without solid) (see, for instance, [65]) but with the tools developed in [104]. A first result of stabilization was obtained in [93] and concerns a fluid contained in bounded cavity where a part of the boundary is modeled by a plate system. The feedback control is a force applied on the whole plate and it allows the author to obtain a local stabilization result around the null state.

To extend these first results of control and stabilization, we first have to make some progress in the analysis of FSIS:

- **Contact:** It is important to understand the behavior of the system when two structures are close, and in particular to understand how to deal with contact problems;
- **Deformable structures:** To handle such structures, we need to develop new ideas and techniques in order to couple two dynamics of infinite dimension and of different nature.

At the same time, we can tackle control problems for simplified models. For instance, in some regimes, the Navier-Stokes system can be replaced by the Stokes system and the Euler system by Laplace's equation

3.2. Inverse problems for heterogeneous systems

The area of inverse problems covers a large class of theoretical and practical issues which are important in many applications (see for instance the books of Isakov [78] or Kaltenbacher, Neubauer, and Scherzer [80]). Roughly speaking, an inverse problem is a problem where one attempts to recover an unknown property of a given system from its response to an external probing signal. For systems described by evolution PDE, one can be interested in the reconstruction from partial measurements of the state (initial, final or current), the inputs (a source term, for instance) or the parameters of the model (a physical coefficient for example). For stationary or periodic problems (i.e. problems where the time dependence is given), one can be interested in determining from boundary data a local heterogeneity (shape of an obstacle, value of a physical coefficient describing the medium, etc.). Such inverse problems are known to be generally ill-posed and their study leads to investigate the following questions:

- *Uniqueness.* The question here is to know whether the measurements uniquely determine the unknown quantity to be recovered. This theoretical issue is a preliminary step in the study of any inverse problem and can be a hard task.
- *Stability.* When uniqueness is ensured, the question of stability, which is closely related to sensitivity, deserves special attention. Stability estimates provides an upper bound for the parameter error given some uncertainty on data. This issue is closely related to the so-called observability inequality in systems theory.
- *Reconstruction.* Inverse problems being usually ill-posed, one needs to develop specific reconstruction algorithms which are robust with respect to noise, disturbances and discretization. A wide class of methods is based on optimization techniques.

In this project, we investigate two classes of inverse problems, which both appear in FSIS and CWS:

1. **Identification for evolution PDE.**

   Driven by applications, the identification problem for systems of infinite dimension described by evolution PDE has known in the last three decades a fast and significant growth. The unknown to be recovered can be the (initial/final) state (e.g. state estimation problems [38], [66], [74], [103] for the design feedback controllers), an input (for instance source inverse problems [35], [48], [59]) or a parameter of the system. These -linear or non linear- problems are generally ill-posed and many regularization approaches have been developed. Among the different methods used for identification, let us mention optimization techniques ([50]), specific one-dimensional techniques (like in [39]) or observer-based methods as in [87].

In the last few years, we have developed observers to solve initial data inverse problems for a class of linear systems of infinite dimension and of the form $\dot{z}(t) = Az(t)$ (A denotes here the generator of a C_0 semigroup) from an output $y(t) = Cz(t)$ measured through a finite time interval. Let us recall that observers (or Luenberger observers [86]) have been introduced in automatic control theory to estimate the state of a dynamical system (of finite dimension) from the knowledge of an output (and, of course, assuming that the initial state is unknown). Roughly speaking, an observer is an auxiliary dynamical system that uses as inputs the available measurements (that is the output of the original system) that converges asymptotically (in time) towards the state of the original system. Observers are very popular in the community of automatic control and have given rise to a wide literature (for more references, see for instance the book by O'Reilly [90] and more recently the one by Trinh and Fernando [106] devoted to functional observers). The generalization of observers (also called estimators or filters in the stochastic framework) to systems of infinite dimension goes back to the seventies (see for instance Bensoussan [42] or Curtain and Zwart [55]) and the theory is definitely less developed than in the case of finite dimension . Using observers, we have proposed in [92], [75] an iterative algorithm to reconstruct initial data from partial measurements for some evolution equations, including the wave and Schrödinger systems (and more generally for skew-adjoint generators). This algorithm also provides a new method to solve source inverse problems, in the case where the source term has a specific structure (separate variables in time-space with known time dependence). We are deepening our activities in this direction by considering more general operators or more general sources and the reconstruction of coefficients for the wave equation. In connection with this last problem, we study the stability in the determination of these coefficients. To achieve this, we use geometrical optics, which is a classical albeit powerful tool to obtain quantitative stability estimates on some inverse problems with a geometrical background, see for instance [41], [40].

2. **Geometric inverse problems.**

We investigate some geometric inverse problems that appear naturally in many applications, like medical imaging and non destructive testing. A typical problem we have in mind is the following: given a domain Ω containing an (unknown) local heterogeneity ω, we consider the boundary value problem of the form

$$\begin{cases} Lu = 0, & (\Omega \setminus \omega) \\ u = f, & (\partial\Omega) \\ Bu = 0, & (\partial\omega) \end{cases}$$

where L is a given partial differential operator describing the physical phenomenon under consideration (typically a second order differential operator), B the (possibly unknown) operator describing the boundary condition on the boundary of the heterogeneity and f the exterior source used to probe the medium. The question is then to recover the shape of ω and/or the boundary operator B from some measurement Mu on the outer boundary $\partial\Omega$. This setting includes in particular inverse scattering problems in acoustics and electromagnetics (in this case Ω is the whole space and the data are far field measurements) and the inverse problem of detecting solids moving in a fluid. It also includes, with slight modifications, more general situations of incomplete data (i.e. measurements on part of the outer boundary) or penetrable inhomogeneities. Our approach to tackle this type of problems is based on the derivation of a series expansion of the input-to-output map of the problem (typically the Dirchlet-to-Neumann map of the problem for the Calderón problem) in terms of the size of the obstacle.

3.3. Numerical analysis and simulation of heterogeneous systems

Within the team, we have developed in the last few years numerical codes for the simulation of FSIS and CWS. We plan to continue our efforts in this direction.

- In the case of FSIS, our main objective is to provide computational tools for the scientific community, essentially to solve academic problems.
- In the case of CWS, our main objective is to build tools general enough to handle industrial problems. Our strong collaboration with Christophe Geuzaine's team in Liege (Belgium) makes this objective credible, through the combination of DDM (Domain Decomposition Methods) and parallel computing.

Below, we explain in detail the corresponding scientific program.

- **Simulation of FSIS:** In order to simulate fluid-structure systems, one has to deal with the fact that the fluid domain is moving and that the two systems for the fluid and for the structure are strongly coupled. To overcome this free boundary problem, three main families of methods are usually applied to numerically compute in an efficient way the solutions of the fluid-structure interaction systems. The first method consists in suitably displacing the mesh of the fluid domain in order to follow the displacement and the deformation of the structure. A classical method based on this idea is the A.L.E. (Arbitrary Lagrangian Eulerian) method: with such a procedure, it is possible to keep a good precision at the interface between the fluid and the structure. However, such methods are difficult to apply for large displacements (typically the motion of rigid bodies). The second family of methods consists in using a *fixed mesh* for both the fluid and the structure and to simultaneously compute the velocity field of the fluid with the displacement velocity of the structure. The presence of the structure is taken into account through the numerical scheme. There are several methods in that direction: immersed boundary method, fictitious domain method, fat boundary method, the Lagrange-Galerkin method. Finally, the third class of methods consists in transforming the set of PDEs governing the flow into a system of integral equations set on the boundary of the immersed structure. Thus, only the surface of the structure is meshed and this mesh moves along with the structure. Notice that this method can be applied only for the flow of particular fluids (ideal fluid or stationary Stokes flow).

  The members of SPHINX have already worked on these three families of numerical methods for FSIS systems with rigid bodies (see e.g. [96], [81], [98], [94], [95], [88]). We plan to work on numerical methods for FSIS systems with non-rigid structures immersed into an incompressible viscous fluid. In particular, we will focus our work on the development and the analysis of numerical schemes and, on the other hand, on the efficient implementation of the corresponding numerical methods.
- **Simulation of CWS:** Solving acoustic or electromagnetic scattering problems can become a tremendously hard task in some specific situations. In the high frequency regime (i.e. for small wavelength), acoustic (Helmholtz's equation) or electromagnetic (Maxwell's equations) scattering problems are known to be difficult to solve while being crucial for industrial applications (e.g. in aeronautics and aerospace engineering). Our particularity is to develop new numerical methods based on the hybridization of standard numerical techniques (like algebraic preconditioners, etc.) with approaches borrowed from asymptotic microlocal analysis. Most particularly, we contribute to building hybrid algebraic/analytical preconditioners and quasi-optimal Domain Decomposition Methods (DDM) [43], [60], [61] for highly indefinite linear systems. Corresponding three-dimensional solvers (like for example GetDDM) will be developed and tested on realistic configurations (e.g. submarines, complete or parts of an aircraft, etc.) provided by industrial partners (Thales, Airbus). Another situation where scattering problems can be hard to solve is the one of dense multiple (acoustic, electromagnetic or elastic) scattering media. Computing waves in such media requires to take into account not only the interaction between the incident wave and the scatterers, but also the effects of the interactions between the scatterers themselves. When the number of scatterers is very large (and possibly for high frequency [37], [36]), specific deterministic or stochastic numerical methods and

algorithms are needed. We introduce new optimized numerical methods for solving such complex configurations. Many applications are related to this kind of problem like e.g. for osteoporosis diagnosis where quantitative ultrasound is a recent and promising technique to detect a risk of fracture. Therefore, numerical simulation of wave propagation in multiple scattering elastic medium in the high frequency regime is a very useful tool for this purpose.

4. Application Domains

4.1. Robotic swimmers

Some companies aim at building biomimetic robots that can swim in an aquarium, as toys (Robotswim) [0] but also for medical objectives. During the last three years, some members of the Inria Project-Team CORIDA [0] (Munnier, Scheid and Takahashi) together with members of the automatics laboratory of Nancy CRAN (Daafouz, Jungers) have initiated an active collaboration (CPER AOC) to construct a swimming ball in a very viscous fluid. This ball has a macroscopic size but since the fluid is highly viscous, its motion is similar to the motion of a nanorobot. Such nanorobots could be used for medical purposes to bring some medicine or perform small surgical operations. In order to get a better understanding of such robotic swimmers, we have obtained control results via shape changes and we have developed simulation tools (see [85], [84], [83]). However, in practice the admissible deformations of the ball are limited since they are realized using piezo-electric actuators. In the next four years, we will take into account these constraints by developing two approaches :

1. Solve the control problem by limiting the set of admissible deformations.
2. Find the "best" location of the actuators, in the sense of being the closest to the exact optimal control.

The main tools for this investigation are the 3D codes that we have developed for simulation of fish into a viscous incompressible fluid (`SUSHI3D`) or into a inviscid incompressible fluid (`SOLEIL`).

4.2. Aeronautics

We will develop robust and efficient solvers for problems arising in aeronautics (or aerospace) like electromagnetic compatibility and acoustic problems related to noise reduction in an aircraft. Our interest for these issues is motivated by our close contacts with companies like Airbus or "Thales Systèmes Aéroportés". We will propose new applications needed by these partners and assist them in integrating these new scientific developments in their home-made solvers. In particular, in collaboration with C. Geuzaine (Université de Liège), we are building a freely available parallel solver based on Domain Decomposition Methods that can handle complex engineering simulations, in terms of geometry, discretization methods as well as physics problems, see http://onelab.info/wiki/GetDDM. Part of this development is done through the grant ANR BECASIM.

5. Highlights of the Year

5.1. Highlights of the Year

The CANUM ("Congrès d'Analyse Numérique", Conference on Numerical Analysis) is the major French-speaking conference on numerical analysis and scientific computing. It is held since 1967 (every year from 1967 to 2000, every two years from 2000). In 2016, the Institut Élie Cartan de Lorraine was in charge of the organization. Most of the members of our team were involved throughout the year. In particular, Karim Ramdani was head of the organizing committee.

[0] The website http://www.robotic-fish.net/ presents a list of several robotic fish that have been built in the last years.
[0] Most members of SPHINX were members of the former Inria project-team CORIDA

6. New Software and Platforms

6.1. GPELab

Gross-Pitaevskii equations Matlab toolbox
KEYWORDS: 3D - Quantum chemistry - 2D
FUNCTIONAL DESCRIPTION

GPELab is a Matlab toolbox developed to help physicists compute ground states or dynamics of quantum systems modeled by Gross-Pitaevskii equations. This toolbox allows the user to define a large range of physical problems (1d-2d-3d equations, general nonlinearities, rotation term, multi-components problems...) and proposes numerical methods that are robust and efficient.

- Contact: Xavier Antoine
- URL: http://gpelab.math.cnrs.fr/

6.2. GetDDM

KEYWORDS: Large scale - 3D - Domain decomposition - Numerical solver
FUNCTIONAL DESCRIPTION

GetDDM combines GetDP and Gmsh to solve large scale finite element problems using optimized Schwarz domain decomposition methods.

- Contact: Xavier Antoine
- URL: http://onelab.info/wiki/GetDDM

6.3. μ-diff

μ-diff is a Matlab toolbox developed with B. Thierry (UPMC, France) for solving 2D multiple scattering problems by a random collection of circular cylinders.

- Contact: Xavier Antoine
- URL: http://mu-diff.math.cnrs.fr/mu-diff/

6.4. Platforms

6.4.1. A software for the efficient assignment of L-INP students

Each year, the 1500 students of the L-INP Collégium (gathering most of the engineering students in Lorraine) have to choose one or several among the 70+ courses. J-F. Scheid, a member of our team, is a faculty member of TELECOM Nancy and developed a solver giving a fair, fast and reliable assignment of the students to the courses. The solver works with integer linear optimization and is written in Python and CBC/COIN-OR.

7. New Results

7.1. Analysis, control and stabilization of heterogeneous systems

Participant: Takéo Takahashi.

In [12], T. Takahashi (with D. Maity and M. Tucsnak, both from Institut de Mathématiques de Bordeaux, France) has considered a free boundary problem modeling the motion of a piston in a viscous gas. The gas-piston system fills a cylinder with fixed extremities, which possibly allow gas from the exterior to penetrate inside the cylinder. The gas is modeled by the 1D compressible Navier-Stokes system and the piston motion is described by the second Newton law. They prove the existence and uniqueness of global in time strong solutions. The main novelty brought in is that the case of nonhomogeneous boundary conditions is considered. Moreover, even for homogeneous boundary conditions, their results require less regularity of the initial data than those obtained in previous works.

In [32], T. Takahashi (with C. Lacave from Institut Fourier, Grenoble, France) has studied the motion of a single disk moving under the influence of a 2D viscous fluid. They deal with the asymptotic as the size of the solid tends to zero. If the density of the solid is independent of the size of the solid, the energy equality is not sufficient to obtain a uniform estimate for the solid velocity. This will be achieved thanks to the optimal $L^p - L^q$ decay estimates of the semigroup associated to the fluid-rigid body system and to a fixed point argument. Next, they deduce the convergence to the solution of the Navier-Stokes equations in $\mathbb{R}^2$.

In [7], T. Takahashi (with C. Bianchini (Dimai, Florence, Italy) and A. Henrot (IECL, Nancy, France)) has tackled a model for the shape of vesicles. In order to do this, they consider a shape optimization problem associated with a Willmore type energy in the plane. More precisely, they study a *Blaschke-Santaló diagram* involving the area, the perimeter and the elastic energy of planar convex bodies. Existence, regularity and geometric properties of solutions to this shape optimization problem are shown.

We have studied the self-propelled motions of a rigid body immersed in a viscous incompressible fluid which fills the exterior domain of the rigid body. The mechanism used by the body to reach the desired motion is modeled through a distribution of velocities at its boundary.

T. Takahashi (with J. San Martín (DIM, Santiago, Chile) and M. Tucsnak (Institut de Mathématiques de Bordeaux, France)) considers in [16] a class of swimmers of low Reynolds number, of prolate spheroidal shape, which can be seen as simplified models of ciliated microorganisms. Within this model, the form of the swimmer does not change, the propelling mechanism consisting in tangential displacements of the material points of swimmer's boundary. Using explicit formulas for the solution of the Stokes equations at the exterior of a translating prolate spheroid the governing equations reduce to a system of ODE's with the control acting in some of its coefficients (bilinear control system). The main theoretical result asserts the exact controllability of the prolate spheroidal swimmer. In the same geometrical situation, they define a concept of efficiency which reduces to the classical one in the case of a spherical swimmer and they consider the optimal control problem of maximizing this efficiency during a stroke. Moreover, they analyse the sensitivity of this efficiency with respect to the eccentricity of the considered spheroid. They provide semi-explicit formulas for the Stokes equations at the exterior of a prolate spheroid, with an arbitrary tangential velocity imposed on the fluid-solid interface. Finally, they use numerical optimization tools to investigate the dependence of the efficiency on the number of inputs and on the eccentricity of the spheroid. The "best" numerical result obtained yields an efficiency of 30.66% with 13 scalar inputs. In the limiting case of a sphere their best numerically obtained efficiency is of 30.4%, whereas the best computed efficiency previously reported in the literature was of 22%.

In [10], T. Takahashi (with T. Hishida (Nagoya University, Japan) and A.L. Silvestre (IST, Lisboa, Portugal)) tackles the stationary case. The fluid motion is modeled by the stationary Navier-Stokes system coupled with two relations for the balance of forces and torques. They prove that there exists a control allowing the rigid body to move with a prescribed rigid velocity provided the velocity is small enough. They also show that since the net force exerted by the fluid to the rigid body vanishes, we have a better summability of the fluid velocity than the classical summability result for the solutions of the stationary Navier-Stokes system in exterior domains.

7.2. Inverse problems for heterogeneous systems

Participants: David Dos Santos Ferreira, Alexandre Munnier, Karim Ramdani, Julie Valein, Jean-Claude Vivalda.

Many inverse problems (IP) appearing in fluid-structure interaction and wave propagation problems have been investigated in the team.

In [14], Munnier and Ramdani consider the 2D inverse problem of recovering the positions and the velocities of slowly moving small rigid disks in a bounded cavity filled with a perfect fluid. Using an integral formulation, they first derive an asymptotic expansion of the DtN map of the problem as the diameters of the disks tend to zero. Then, combining a suitable choice of exponential type data and the DORT method (French acronym for Diagonalization of the Time Reversal Operator), a reconstruction method for the unknown positions and velocities is proposed. Let us emphasize here that this reconstruction method uses in the context of fluid-structure interaction problems a method which is usually used for waves inverse scattering (the DORT method).

In [13], Munnier and Ramdani propose a new method to tackle a geometric inverse problem related to Calderón's inverse problem. More precisely, they propose an explicit reconstruction formula for the cavity inverse problem using conformal mapping. This formula is derived by combining two ingredients: a new factorization result of the DtN map and the so-called generalized Pólia-Szegö tensors of the cavity.

In [9], P. Caro (Department of Mathematics and Statistics, Helsinki, Finland), D. Dos Santos Ferreira and Alberto Ruiz (Instituto de Ciencias Matematicas, Madrid, Spain) obtained stability estimates for potentials in a Schrödinger equation in dimension higher than 3 from the associated Dirichlet-to-Neumann map with partial data. The estimates are of log-log type and represent a quantitative version of the uniqueness result of Kenig, Sjöstrand and Uhlmann. The proof is based on a reduction to a stability estimate on the attenuated geodesic ray transform on the hypersphere.

In [15], Ramdani, Tucsnak (Institut de Mathématiques de Bordeaux, France) and Valein tackle a state estimation problem for a system of infinite dimension arising in population dynamics (a linear model for age-structured populations with spatial diffusion). Assume the initial state to be unknown, the considered inverse problem is to estimate asymptotically on time the state of the system from a locally distributed observation in both age and space. This is done by designing a Luenberger observer for the system, taking advantage of the particular spectral structure of the problem (the system has a finite number of unstable eigenvalues).

In [2], Ammar (Faculté des Sciences de Sfax, Tunisia), Massaoud (Faculté des Sciences de Sfax, Tunisia) and Vivalda characterize the globally Lipschitz continuous systems defined on $\mathbb{R}^n$ whose observability is preserved under time sampling.

7.3. Numerical analysis and simulation of heterogeneous systems

Participants: Xavier Antoine, Mohamed El Bouajaji, Karim Ramdani, Qinglin Tang, Julie Valein, Chi-Ting Wu.

In optics, metamaterials (also known as negative or left-handed materials), have known a growing interest in the last two decades. These artificial composite materials exhibit the property of having negative dielectric permittivity and magnetic permeability in a certain range of frequency, leading hence to materials with negative refractive index and super lens effects. In [8], Bunoiu (IECL, Metz, France) and Ramdani consider a complex wave system involving such materials. More precisely, they consider a periodic homogenization problem involving two isotropic materials with conductivities of different signs: a classical material and a metamaterial (or negative material). Combining the $\mathbf{T}-$coercivity approach and the unfolding method for homogenization, they prove well-posedness results for the initial and the homogenized problems and obtain a convergence result, provided that the contrast between the two conductivities is large enough (in modulus).

In [18], Tucsnak (Institut de Mathématiques de Bordeaux, France), Valein and Wu study the numerical approximation of the solutions of a class of abstract parabolic time-optimal control problems with unbounded control operator. Our main results assert that, provided that the target is a closed ball centered at the origin and of positive radius, the optimal time and the optimal controls of the approximate time optimal problems converge (in appropriate norms) to the optimal time and to the optimal controls of the original problem. In order to prove our main theorem, we provide a nonsmooth data error estimate for abstract parabolic systems.

In [4], Antoine and Lorin (School of Mathematics and Statistics, Ottawa, and CRM, Montréal, Canada) analyze the convergence of optimized Schwarz domain decomposition methods for the simulation of the time-domain Schrödinger equation with high-order local transmission conditions.

In [5], Antoine, Tang and Zhang (WPI, Austria and IRMAR, France) develop some spectral methods for computing the ground states and dynamics of space fractional Gross-Pitaevskii equations arising in the modeling of fractional Bose-Einstein equations with long-range nonlinear interactions. In addition, we also state some existence and uniqueness properties for the ground states of such equations, and prove some dynamical laws.

In [6], Bao (Department of Mathematics, Singapore), Tang and Zhang (WPI, Austria and IRMAR, France) develop a new efficient and spectrally accurate numerical for computing the ground state and dynamics of dipolar Bose-Einstein condensates. They pay a particular attention to the computation of the nonlinear nonlocal interactions through the use of the nonuniform fast Fourier transform.

In [22], Antoine, Levitt (CERMICS, France) and Tang derive a highly accurate and efficient new numerical method for computing the ground states of the fast rotating Gross-Pitaevskii equation. The method is based on a preconditioned nonlinear conjugate gradient method which leads to a high gain compared to most recent approaches.

In [26], Bao (Department of Mathematics, Singapore), Cai (Department of mathematics Purdue University, USA and CSRC, Beijing, China), Jia (Department of Mathematics, Singapore), Tang develop a uniformly accurate multiscale time integrator in conjunction with a spectral method for computing the dynamics of the nonrelativistic Dirac equation. The same authors develop and compare, in [27], some new numerical methods for the simulation of the Dirac equation when the nonrelativistic regime is considered.

The article [17] is devoted to explain how the open finite element solver GetDDM works. The mathematical methods behind GetDDM are optimized Schwarz domain decomposition methods with well-designed transmission boundary conditions. GetDDM allows to solve large scale high frequency wave problems (e.g. acoustics, electromagnetism, elasticity problems) on large clusters. This papers explains through examples and scripts how GetDDM must be used. GetDDM is a result of a long term collaboration between Xavier Antoine and Christophe Geuzaine (University of Liège).

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Grants with Industry

The Ph.D thesis of Boris Caudron is funded through a CIFRE contract with Thalès and a contract with the IECL. The goal of the Ph.D. thesis is to design new coupling techniques between integral equation methods and the finite element method for solving electromagnetic scattering problems. The advisors are Xavier Antoine (Sphinx) and Christophe Geuzaine (University of Liège).

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. ANR

- David Dos Santos Ferreira is the coordinator (PI) of a Young Researcher Program of the French National Research Agency (ANR) :
  Project Acronym : iproblems
  Project Title : Inverse Problems
  Coordinator : David Dos Santos Ferreira
  Duration : 48 months (2013-2017)
- Takéo Takahashi is the coordinator (PI) of a Researcher Program of the French National Research Agency (ANR) :
  Project Acronym : IFSMACS
  Project Title : Fluid-Structure Interaction: Modeling, Analysis, Control and Simulation
  Coordinator: Takéo Takahashi
  Duration : 48 months (starting on October 1st, 2016)
  URL: http://ifsmacs.iecl.univ-lorraine.fr/

- Xavier Antoine is member of the project TECSER funded by the French armament procurement agency in the framework of the Specific Support for Research Works and Innovation Defense (ASTRID 2013 program) operated by the French National Research Agency.
Project Acronym: TECSER
Project Title : Nouvelles techniques de résolution adaptées à la simulation haute performance pour le calcul SER
Coordinator: Stéphane Lanteri (Inria, NACHOS project-team)
Duration: 36 months (starting on May 1st, 2014)
URL: http://www-sop.inria.fr/nachos/projects/tecser/index.php/Main/HomePage
- Xavier Antoine is member of the project BoND.
Project Acronym: BoND
Project Title: Boundaries, Numerics and Dispersion.
Coordinator: Sylvie Benzoni (Institut Camille Jordan, Lyon, France)
Duration: 48 months (starting on October 15th, 2013)
URL: http://bond.math.cnrs.fr
- Xavier Antoine is the local coordinator of the ANR project BECASIM.
Project acronym: BECASIM
Project Title: Bose-Einstein Condensates: Advanced SIMulation Deterministic and Stochastic Computational Models, HPC Implementation, Simulation of Experiments.
Coordinator: Ionut Danaila (Université de Rouen, France)
Duration: 48 months (plus an extension of 12 months, until November 2017)
URL: http://becasim.math.cnrs.fr

9.1.2. CNRS

Thomas Chambrion is the coordinator of the Research Project from CNRS Inphynity "DISQUO" (5300 euros, 2016).

9.2. International Initiatives

9.2.1. Participation in Other International Programs

Within the PHC Utique programme, a project of French-Tunisian collaboration involving some members of our team has been selected by Campus France. The exact amount of the budget is not known yet and will be comprised between 9000 and 16000 euros.

9.3. International Research Visitors

9.3.1. Visits to International Teams

Xavier ANTOINE has been a visitor of the Beijing CSRC for 4 weeks during the summer 2016.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General chair, scientific chair

Xavier Antoine was a member of the scientific committee of Waves 2017, University of Minneapolis, USA.

10.1.1.2. Member of the Organizing Committees

Several members of the team were involved in the organization of the 43rd national conference CANUM 2016 (http://smai.emath.fr/canum2016/). In particular, Karim Ramdani was the head of the Organizing Committee.

Xavier Antoine was co-organizer of Colloque Couplages numériques, hold in September 27-29, 2016, in Nice, France. http://math.unice.fr/~massonr/CouplagesNumeriques/index.php

Julie Valein organized a day Fédération Charles Hermite “Estimation for dynamical systems" (06/10/2016)

10.1.2. Scientific Events Selection

10.1.2.1. Reviewer

Thomas Chambrion is a reviewer for the American Control Conference and the Conference on Decision and Control.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

Jean-Claude Vivalda is a member of the editorial board of the *Journal of Dynamical and Control Systems*.

10.1.3.2. Reviewer - Reviewing Activities

Most of the members of our team are regular reviewer for major publications in the field of control.

- Thomas Chambrion is a reviewer for SICON, IEEE TAC, Automatica, International Journal of Control, MCMS.
- Julie Valein is a reviewer for SICON, ESAIM COCV.
- Jean-Claude Vivalda is a reviewer for SICON and for the Mathematical Reviews.

10.1.4. Invited Talks

Julie Valein was invited to

- LMV seminar, Versailles, 14 janvier 2016
- Mathematics-Automatic meeting, IECL – CRAN, Nancy, 28 June, 2016
- Conference « Stability of non-conservative systems », Valenciennes, 4-7 July 2016

Xavier Antoine was invited to

- Seminar, Bale University, December 2016.
- Seminar, Beijing University, July 2016.

10.1.5. Scientific Expertise

Julie Valein was a member of several “Comité de selection”:

- for an associate professor position at École des Mines de Nancy;
- for an associate professor position at Université Lyon 1;
- for a teaching position at École des Sciences et Techniques de l'Ingénieur de Nancy.

Thomas Chambrion belongs to the selection panel for the Natural Sciences and Engineering Research Council of Canada.

10.1.6. Research Administration

- Xavier Antoine has been head of IECL since September 2015.
- David Dos Santos has been head of IECL PDE team since September 2014.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Most of the members of the team have a teaching position at Université de Lorraine.

Xavier Antoine teaches at Mines Nancy and ENSEM (Université de Lorraine), L3-M1, 96 hours.

Thomas Chambrion teaches at ESSTIN (Université de Lorraine), L1-L2, 192 hours.

David Dos Santos Ferreira teaches at UFR STMIA (Université de Lorraine), 192 hours.

Alexandre Munnier teaches at UFR STMIA (Université de Lorraine), 192 hours.

Jean-François Scheid teaches at Telecom Nancy (Université de Lorraine), 192 hours.

Julie Valein teaches at ESSTIN (Université de Lorraine), L1-L2, 192 hours.

10.2.2. Supervision

PhD in progress : Boris Caudron, CIFRE thesis with Thales, Coupling between integral equations/finite element for the numerical solution by domain decomposition methods of wave scattering problems, since June 2015, Xavier Antoine and Christophe Guezaine.

PhD in progress : Alessandro Duca, controllability of bilinear Schrödinger equations, since September 2015, Nabile Boussaïd and Thomas Chambrion.

10.2.3. Juries

Xavier Antoine was a referee for the Ph.D. thesis of P. Rammaciotti Morales (Ecole Polytechnique), and Marc Bakry (ENSTA).

Thomas Chambrion was referee of the PhD thesis of Leo Van Damme (Université de Bourgogne).

10.3. Popularization

Karim Ramdani has given several talks at Université de Lorraine to raise researchers awareness on the risks of author-pays publication model (for more information on economic models of scientific publishing, see http://iecl.univ-lorraine.fr/~Karim.Ramdani/KR_BIB/AUTEURS.html).

Thomas Chambrion gave a presentation of applied mathematics at Lycée Poincaré (Nancy) in April 2016.

11. Bibliography

Publications of the year

Articles in International Peer-Reviewed Journal

[1] H. Alzubaidi, X. Antoine, C. Chniti. *Formulation and accuracy of on-surface radiation conditions for acoustic multiple scattering problems*, in "Applied Mathematics and Computation", 2016, vol. 277, p. 82-100, https://hal.archives-ouvertes.fr/hal-01244517.

[2] S. Ammar, M. Massaoud, J.-C. Vivalda. *Observability Under Sampling for Nonlinear Systems*, in "Asian Journal of Control", July 2016, vol. 18, n° 4, 10 [*DOI :* 10.1002/asjc.1284], https://hal.inria.fr/hal-01264249.

[3] X. ANTOINE, C. BESSE, V. RISPOLI.*High-order IMEX-spectral schemes for computing the dynamics of systems of nonlinear Schrödinger /Gross-Pitaevskii equations*, in "Journal of Computational Physics", December 2016, vol. 327, p. 252–269 [*DOI :* 10.1016/J.JCP.2016.09.020], https://hal.archives-ouvertes.fr/hal-01271463.

[4] X. ANTOINE, E. LORIN.*Lagrange–Schwarz Waveform Relaxation domain decomposition methods for linear and nonlinear quantum wave problems*, in "Applied Mathematics Letters", 2016, vol. 57, p. 38-45 [*DOI :* 10.1016/J.AML.2015.12.012], https://hal.archives-ouvertes.fr/hal-01244354.

[5] X. ANTOINE, Q. TANG, Y. ZHANG.*On the ground states and dynamics of space fractional nonlinear Schrödinger/Gross-Pitaevskii equations with rotation term and nonlocal nonlinear interactions*, in "Journal of Computational Physics", 2016, vol. 325, p. 74-97 [*DOI :* 10.1016/J.JCP.2016.08.009], https://hal.archives-ouvertes.fr/hal-01244364.

[6] W. BAO, Q. TANG, Y. ZHANG.*Accurate and efficient numerical methods for computing ground states and dynamics of dipolar Bose-Einstein condensates via the nonuniform FFT*, in "Communications in Computational Physics", 2016, vol. 19, n^{o} 5, p. 1141-1166 [*DOI :* 10.4208/CICP.SCPDE14.37S], https://hal.archives-ouvertes.fr/hal-01273317.

[7] C. BIANCHINI, A. HENROT, T. TAKAHASHI.*Elastic energy of a convex body*, in "Mathematische Nachrichten", 2016, vol. 289, n^{o} 5-6, p. 546-574 [*DOI :* 10.1002/MANA201400256], https://hal.archives-ouvertes.fr/hal-01011979.

[8] R. BUNOIU, K. RAMDANI.*Homogenization of materials with sign changing coefficients*, in "Communications in Mathematical Sciences", 2016, vol. 14, n^{o} 4, p. 1137-1154 [*DOI :* 10.4310/CMS.2016.V14.N4.A13], https://hal.inria.fr/hal-01162225.

[9] D. DOS SANTOS FERREIRA, P. CARO, A. RUIZ.*Stability estimates for the Calderón problem with partial data*, in "Journal of Differential Equations", February 2016, vol. 260, n^{o} 3 [*DOI :* 10.1016/J.JDE.2015.10.007], https://hal.archives-ouvertes.fr/hal-01251717.

[10] T. HISHIDA, A. L. SILVESTRE, T. TAKAHASHI.*A boundary control problem for the steady self-propelled motion of a rigid body in a Navier-Stokes fluid*, in "Annales de l'Institut Henri Poincaré (C) Non Linear Analysis", 2017, https://hal.archives-ouvertes.fr/hal-01205210.

[11] E. LORIN, X. YANG, X. ANTOINE.*Frozen Gaussian Approximation based domain decomposition methods for the linear Schrödinger equation beyond the semi-classical regime*, in "Journal of Computational Physics", 2016, vol. 315, p. 221-237, https://hal.archives-ouvertes.fr/hal-01244430.

[12] D. MAITY, T. TAKAHASHI, M. TUCSNAK.*Analysis of a System Modelling The Motion of a Piston in a Viscous Gas*, in "Journal of Mathematical Fluid Mechanics", 2016, https://hal.archives-ouvertes.fr/hal-01285089.

[13] A. MUNNIER, K. RAMDANI.*Conformal mapping for cavity inverse problem: an explicit reconstruction formula*, in "Applicable Analysis", 2016 [*DOI :* 10.1080/00036811.2016.1208816], https://hal.inria.fr/hal-01196111.

[14] A. MUNNIER, K. RAMDANI.*On the detection of small moving disks in a fluid*, in "SIAM Journal on Applied Mathematics", 2016, vol. 76, n^{o} 1, p. 159-177 [*DOI :* 10.1137/141001226], https://hal.inria.fr/hal-01098067.

[15] K. Ramdani, M. Tucsnak, J. Valein.*Detectability and state estimation for linear age-structured population diffusion models*, in "ESAIM: Mathematical Modelling and Numerical Analysis", 2016, vol. 50, n° 6, p. 1731-1761 [*DOI :* 10.1051/m2an/2016002], https://hal.inria.fr/hal-01140166.

[16] J. San Martin, T. Takahashi, M. Tucsnak.*An optimal control approach to ciliary locomotion*, in "Mathematical Control and Related Fields", 2016, https://hal.archives-ouvertes.fr/hal-01062663.

[17] B. Thierry, A. Vion, S. Tournier, M. El Bouajaji, D. Colignon, N. Marsic, X. Antoine, C. Geuzaine. *GetDDM: an open framework for testing Schwarz methods for time-harmonic wave problems*, in "Computer Physics Communications", 2016, vol. 203, p. 309-330, https://hal.archives-ouvertes.fr/hal-01244511.

[18] M. Tucsnak, J. Valein, C.-T. Wu.*Finite dimensional approximations for a class of infinite dimensional time optimal control problems*, in "International Journal of Control", 2016, p. 1 - 13 [*DOI :* 10.1080/00207179.2016.1228122], https://hal.archives-ouvertes.fr/hal-01393258.

Scientific Books (or Scientific Book chapters)

[19] X. Antoine, C. Geuzaine.*Optimized Schwarz Domain Decomposition Methods for Scalar and Vector Helmholtz Equations*, in "Modern Solvers for Helmholtz Problems", J. T. D. Lahaye, K. Vuik (editors), Lecture Notes in Geosystems Mathematics and Computing, Birkhauser, 2016, p. 1-24, https://hal.archives-ouvertes.fr/hal-01276808.

Other Publications

[20] J. AMALBERTI, X. Antoine, P. Burnard.*Plinian eruption timescale: a numerical modelling investigation*, February 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01273172.

[21] X. Antoine, C. Besse, R. Duboscq, V. Rispoli.*Acceleration of the imaginary time method for spectrally computing the stationary states of Gross-Pitaevskii equations*, August 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01356227.

[22] X. Antoine, A. Levitt, Q. Tang.*Efficient spectral computation of the stationary states of rotating Bose-Einstein condensates by the preconditioned nonlinear conjugate gradient method*, November 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01393094.

[23] X. Antoine, E. Lorin.*Multilevel preconditioning techniques for Schwarz waveform relaxation domain decomposition methods for real-and imaginary-time nonlinear Schrödinger equations*, 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01266021.

[24] X. Antoine, E. Lorin, Q. Tang.*A Friendly Review of Absorbing Boundary Conditions and Perfectly Matched Layers for Classical and Relativistic Quantum Waves Equations*, September 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01374183.

[25] M. Badra, T. Takahashi.*Feedback boundary stabilization of 2d fluid-structure interaction systems*, September 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01370000.

[26] W. Bao, Y. Cai, X. Jia, Q. Tang.*A uniformly accurate (UA) multiscale time integrator pseudospectral method for the Dirac equation in the nonrelativistic limit regime*, February 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01273351.

[27] W. Bao, Y. Cai, X. Jia, Q. Tang.*Numerical methods and comparison for the Dirac equation in the nonrelativistic limit regime*, February 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01277107.

[28] N. Burq, D. Dos Santos Ferreira, K. Krupchyk.*From semiclassical Strichartz estimates to uniform L^p resolvent estimates on compact manifolds*, January 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01251701.

[29] L. Bălilescu, J. San Martín, T. Takahashi.*Fluid-structure interaction system with Coulomb's law*, October 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01386574.

[30] L. Bălilescu, J. San Martín, T. Takahashi.*On the Navier–Stokes system with the Coulomb friction law boundary condition*, November 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01393709.

[31] T. Khajah, X. Antoine, S. P. Bordas.*Isogeometric finite element analysis of time-harmonic exterior acoustic scattering problems*, October 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01377485.

[32] C. Lacave, T. Takahashi.*Small moving rigid body into a viscous incompressible fluid*, November 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01169436.

[33] T. Takahashi.*Boundary local null controllability of the Kuramoto-Sivashinsky equation*, September 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01373201.

[34] J. Zhang, D. Li, X. Antoine.*Efficient numerical computation of time-fractional nonlinear Schrödinger equations in unbounded domain*, December 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01422725.

References in notes

[35] C. Alves, A. L. Silvestre, T. Takahashi, M. Tucsnak.*Solving inverse source problems using observability. Applications to the Euler-Bernoulli plate equation*, in "SIAM J. Control Optim.", 2009, vol. 48, n^o 3, p. 1632-1659.

[36] X. Antoine, K. Ramdani, B. Thierry.*Wide Frequency Band Numerical Approaches for Multiple Scattering Problems by Disks*, in "Journal of Algorithms & Computational Technologies", 2012, vol. 6, n^o 2, p. 241–259.

[37] X. Antoine, C. Geuzaine, K. Ramdani.*Computational Methods for Multiple Scattering at High Frequency with Applications to Periodic Structures Calculations*, in "Wave Propagation in Periodic Media", Progress in Computational Physics, Vol. 1, Bentham, 2010, p. 73-107.

[38] D. Auroux, J. Blum.*A nudging-based data assimilation method : the Back and Forth Nudging (BFN) algorithm*, in "Nonlin. Proc. Geophys.", 2008, vol. 15, n^o 305-319.

[39] M. I. Belishev, S. A. Ivanov.*Reconstruction of the parameters of a system of connected beams from dynamic boundary measurements*, in "Zap. Nauchn. Sem. S.-Peterburg. Otdel. Mat. Inst. Steklov. (POMI)", 2005, vol. 324, n^o Mat. Vopr. Teor. Rasprostr. Voln. 34, p. 20–42, 262.

[40] M. BELLASSOUED, D. DOS SANTOS FERREIRA.*Stability estimates for the anisotropic wave equation from the Dirichlet-to-Neumann map*, in "Inverse Probl. Imaging", 2011, vol. 5, n^{o} 4, p. 745–773, http://dx.doi.org/10.3934/ipi.2011.5.745.

[41] M. BELLASSOUED, D. D. S. FERREIRA.*Stable determination of coefficients in the dynamical anisotropic Schrödinger equation from the Dirichlet-to-Neumann map*, in "Inverse Problems", 2010, vol. 26, n^{o} 12, 125010, 30, http://dx.doi.org/10.1088/0266-5611/26/12/125010.

[42] A. BENSOUSSAN.*Filtrage optimal des systèmes linéaires*, Méthodes mathématiques de l'informatique, Dunod, Paris, 1971.

[43] Y. BOUBENDIR, X. ANTOINE, C. GEUZAINE.*A Quasi-Optimal Non-Overlapping Domain Decomposition Algorithm for the Helmholtz Equation*, in "Journal of Computational Physics", 2012, vol. 2, n^{o} 231, p. 262-280.

[44] M. BOULAKIA.*Existence of weak solutions for an interaction problem between an elastic structure and a compressible viscous fluid*, in "J. Math. Pures Appl. (9)", 2005, vol. 84, n^{o} 11, p. 1515–1554, http://dx.doi.org/10.1016/j.matpur.2005.08.004.

[45] M. BOULAKIA, S. GUERRERO.*Regular solutions of a problem coupling a compressible fluid and an elastic structure*, in "J. Math. Pures Appl. (9)", 2010, vol. 94, n^{o} 4, p. 341–365, http://dx.doi.org/10.1016/j.matpur.2010.04.002.

[46] M. BOULAKIA, A. OSSES.*Local null controllability of a two-dimensional fluid-structure interaction problem*, in "ESAIM Control Optim. Calc. Var.", 2008, vol. 14, n^{o} 1, p. 1–42, http://dx.doi.org/10.1051/cocv:2007031.

[47] M. BOULAKIA, E. SCHWINDT, T. TAKAHASHI.*Existence of strong solutions for the motion of an elastic structure in an incompressible viscous fluid*, in "Interfaces Free Bound.", 2012, vol. 14, n^{o} 3, p. 273–306, http://dx.doi.org/10.4171/IFB/282.

[48] G. BRUCKNER, M. YAMAMOTO.*Determination of point wave sources by pointwise observations: stability and reconstruction*, in "Inverse Problems", 2000, vol. 16, n^{o} 3, p. 723–748.

[49] A. CHAMBOLLE, B. DESJARDINS, M. J. ESTEBAN, C. GRANDMONT.*Existence of weak solutions for the unsteady interaction of a viscous fluid with an elastic plate*, in "J. Math. Fluid Mech.", 2005, vol. 7, n^{o} 3, p. 368–404, http://dx.doi.org/10.1007/s00021-004-0121-y.

[50] C. CHOI, G. NAKAMURA, K. SHIROTA.*Variational approach for identifying a coefficient of the wave equation*, in "Cubo", 2007, vol. 9, n^{o} 2, p. 81–101.

[51] C. CONCA, J. SAN MARTÍN, M. TUCSNAK.*Existence of solutions for the equations modelling the motion of a rigid body in a viscous fluid*, in "Comm. Partial Differential Equations", 2000, vol. 25, n^{o} 5-6, p. 1019–1042, http://dx.doi.org/10.1080/03605300008821540.

[52] D. COUTAND, S. SHKOLLER.*Motion of an elastic solid inside an incompressible viscous fluid*, in "Arch. Ration. Mech. Anal.", 2005, vol. 176, n^{o} 1, p. 25–102, http://dx.doi.org/10.1007/s00205-004-0340-7.

[53] D. COUTAND, S. SHKOLLER.*The interaction between quasilinear elastodynamics and the Navier-Stokes equations*, in "Arch. Ration. Mech. Anal.", 2006, vol. 179, n$^{\text{o}}$ 3, p. 303–352, http://dx.doi.org/10.1007/s00205-005-0385-2.

[54] P. CUMSILLE, T. TAKAHASHI.*Wellposedness for the system modelling the motion of a rigid body of arbitrary form in an incompressible viscous fluid*, in "Czechoslovak Math. J.", 2008, vol. 58(133), n$^{\text{o}}$ 4, p. 961–992, http://dx.doi.org/10.1007/s10587-008-0063-2.

[55] R. F. CURTAIN, H. ZWART.*An introduction to infinite-dimensional linear systems theory*, Texts in Applied Mathematics, Springer-Verlag, New York, 1995, vol. 21.

[56] B. DESJARDINS, M. J. ESTEBAN.*On weak solutions for fluid-rigid structure interaction: compressible and incompressible models*, in "Comm. Partial Differential Equations", 2000, vol. 25, n$^{\text{o}}$ 7-8, p. 1399–1413, http://dx.doi.org/10.1080/03605300008821553.

[57] B. DESJARDINS, M. J. ESTEBAN.*Existence of weak solutions for the motion of rigid bodies in a viscous fluid*, in "Arch. Ration. Mech. Anal.", 1999, vol. 146, n$^{\text{o}}$ 1, p. 59–71, http://dx.doi.org/10.1007/s002050050136.

[58] B. DESJARDINS, M. J. ESTEBAN, C. GRANDMONT, P. LE TALLEC.*Weak solutions for a fluid-elastic structure interaction model*, in "Rev. Mat. Complut.", 2001, vol. 14, n$^{\text{o}}$ 2, p. 523–538.

[59] A. EL BADIA, T. HA-DUONG.*Determination of point wave sources by boundary measurements*, in "Inverse Problems", 2001, vol. 17, n$^{\text{o}}$ 4, p. 1127–1139.

[60] M. EL BOUAJAJI, X. ANTOINE, C. GEUZAINE.*Approximate Local Magnetic-to-Electric Surface Operators for Time-Harmonic Maxwell's Equations*, in "Journal of Computational Physics", 2015, vol. 15, n$^{\text{o}}$ 279, p. 241-260.

[61] M. EL BOUAJAJI, B. THIERRY, X. ANTOINE, C. GEUZAINE.*A quasi-optimal domain decomposition algorithm for the time-harmonic Maxwell's equations*, in "Journal of Computational Physics", 2015, vol. 294, n$^{\text{o}}$ 1, p. 38-57 [*DOI :* 10.1016/J.JCP.2015.03.041], https://hal.archives-ouvertes.fr/hal-01095566.

[62] E. FEIREISL.*On the motion of rigid bodies in a viscous compressible fluid*, in "Arch. Ration. Mech. Anal.", 2003, vol. 167, n$^{\text{o}}$ 4, p. 281–308, http://dx.doi.org/10.1007/s00205-002-0242-5.

[63] E. FEIREISL.*On the motion of rigid bodies in a viscous incompressible fluid*, in "J. Evol. Equ.", 2003, vol. 3, n$^{\text{o}}$ 3, p. 419–441, Dedicated to Philippe Bénilan, http://dx.doi.org/10.1007/s00028-003-0110-1.

[64] E. FEIREISL, M. HILLAIRET, Š. NEČASOVÁ.*On the motion of several rigid bodies in an incompressible non-Newtonian fluid*, in "Nonlinearity", 2008, vol. 21, n$^{\text{o}}$ 6, p. 1349–1366, http://dx.doi.org/10.1088/0951-7715/21/6/012.

[65] E. FERNÁNDEZ-CARA, S. GUERRERO, O. Y. IMANUVILOV, J.-P. PUEL.*Local exact controllability of the Navier-Stokes system*, in "J. Math. Pures Appl. (9)", 2004, vol. 83, n$^{\text{o}}$ 12, p. 1501–1542.

[66] E. FRIDMAN.*Observers and initial state recovering for a class of hyperbolic systems via Lyapunov method*, in "Automatica", 2013, vol. 49, n$^{\text{o}}$ 7, p. 2250 - 2260.

[67] G. P. GALDI. *Slow motion of a body in a viscous incompressible fluid with application to particle sedimentation*, in "Recent developments in partial differential equations", Quad. Mat., Dept. Math., Seconda Univ. Napoli, Caserta, 1998, vol. 2, p. 1–35.

[68] G. P. GALDI, A. L. SILVESTRE. *Strong solutions to the problem of motion of a rigid body in a Navier-Stokes liquid under the action of prescribed forces and torques*, in "Nonlinear problems in mathematical physics and related topics, I", Int. Math. Ser. (N. Y.), Kluwer/Plenum, New York, 2002, vol. 1, p. 121–144 [*DOI :* 10.1007/978-1-4615-0777-2-8], http://dx.doi.org/10.1007/978-1-4615-0777-2_8.

[69] G. P. GALDI, A. L. SILVESTRE. *The steady motion of a Navier-Stokes liquid around a rigid body*, in "Arch. Ration. Mech. Anal.", 2007, vol. 184, n° 3, p. 371–400, http://dx.doi.org/10.1007/s00205-006-0026-4.

[70] G. P. GALDI, A. L. SILVESTRE. *On the motion of a rigid body in a Navier-Stokes liquid under the action of a time-periodic force*, in "Indiana Univ. Math. J.", 2009, vol. 58, n° 6, p. 2805–2842, http://dx.doi.org/10.1512/iumj.2009.58.3758.

[71] O. GLASS, F. SUEUR. *The movement of a solid in an incompressible perfect fluid as a geodesic flow*, in "Proc. Amer. Math. Soc.", 2012, vol. 140, n° 6, p. 2155–2168, http://dx.doi.org/10.1090/S0002-9939-2011-11219-X.

[72] C. GRANDMONT, Y. MADAY. *Existence for an unsteady fluid-structure interaction problem*, in "M2AN Math. Model. Numer. Anal.", 2000, vol. 34, n° 3, p. 609–636, http://dx.doi.org/10.1051/m2an:2000159.

[73] M. D. GUNZBURGER, H.-C. LEE, G. A. SEREGIN. *Global existence of weak solutions for viscous incompressible flows around a moving rigid body in three dimensions*, in "J. Math. Fluid Mech.", 2000, vol. 2, n° 3, p. 219–266, http://dx.doi.org/10.1007/PL00000954.

[74] G. HAINE. *Recovering the observable part of the initial data of an infinite-dimensional linear system with skew-adjoint generator*, in "Mathematics of Control, Signals, and Systems", 2014, vol. 26, n° 3, p. 435-462.

[75] G. HAINE, K. RAMDANI. *Reconstructing initial data using observers: error analysis of the semi-discrete and fully discrete approximations*, in "Numer. Math.", 2012, vol. 120, n° 2, p. 307-343.

[76] J. HOUOT, A. MUNNIER. *On the motion and collisions of rigid bodies in an ideal fluid*, in "Asymptot. Anal.", 2008, vol. 56, n° 3-4, p. 125–158.

[77] O. Y. IMANUVILOV, T. TAKAHASHI. *Exact controllability of a fluid-rigid body system*, in "J. Math. Pures Appl. (9)", 2007, vol. 87, n° 4, p. 408–437, http://dx.doi.org/10.1016/j.matpur.2007.01.005.

[78] V. ISAKOV. *Inverse problems for partial differential equations*, Applied Mathematical Sciences, Second, Springer, New York, 2006, vol. 127.

[79] N. V. JUDAKOV. *The solvability of the problem of the motion of a rigid body in a viscous incompressible fluid*, in "Dinamika Splošn. Sredy", 1974, n° Vyp. 18 Dinamika Zidkost. so Svobod. Granicami, p. 249–253, 255.

[80] B. KALTENBACHER, A. NEUBAUER, O. SCHERZER. *Iterative regularization methods for nonlinear ill-posed problems*, Radon Series on Computational and Applied Mathematics, Walter de Gruyter GmbH & Co. KG, Berlin, 2008, vol. 6.

[81] G. LEGENDRE, T. TAKAHASHI.*Convergence of a Lagrange-Galerkin method for a fluid-rigid body system in ALE formulation*, in "M2AN Math. Model. Numer. Anal.", 2008, vol. 42, n^{o} 4, p. 609–644, http://dx.doi.org/10.1051/m2an:2008020.

[82] J. LEQUEURRE.*Existence of strong solutions to a fluid-structure system*, in "SIAM J. Math. Anal.", 2011, vol. 43, n^{o} 1, p. 389–410, http://dx.doi.org/10.1137/10078983X.

[83] J. LOHÉAC, A. MUNNIER.*Controllability of 3D low Reynolds number swimmers*, in "ESAIM Control Optim. Calc. Var.", 2014, vol. 20, n^{o} 1, p. 236–268, http://dx.doi.org/10.1051/cocv/2013063.

[84] J. LOHÉAC, J.-F. SCHEID.*Time optimal control for a nonholonomic system with state constraint*, in "Math. Control Relat. Fields", 2013, vol. 3, n^{o} 2, p. 185–208, http://dx.doi.org/10.3934/mcrf.2013.3.185.

[85] J. LOHÉAC, J.-F. SCHEID, M. TUCSNAK.*Controllability and time optimal control for low Reynolds numbers swimmers*, in "Acta Appl. Math.", 2013, vol. 123, p. 175–200, http://dx.doi.org/10.1007/s10440-012-9760-9.

[86] D. LUENBERGER.*Observing the state of a linear system*, in "IEEE Trans. Mil. Electron.", 1964, vol. MIL-8, p. 74-80.

[87] P. MOIREAU, D. CHAPELLE, P. LE TALLEC.*Joint state and parameter estimation for distributed mechanical systems*, in "Computer Methods in Applied Mechanics and Engineering", 2008, vol. 197, p. 659–677.

[88] A. MUNNIER, B. PINÇON.*Locomotion of articulated bodies in an ideal fluid: 2D model with buoyancy, circulation and collisions*, in "Math. Models Methods Appl. Sci.", 2010, vol. 20, n^{o} 10, p. 1899–1940, http://dx.doi.org/10.1142/S0218202510004829.

[89] A. MUNNIER, E. ZUAZUA.*Large time behavior for a simplified N-dimensional model of fluid-solid interaction*, in "Comm. Partial Differential Equations", 2005, vol. 30, n^{o} 1-3, p. 377–417, http://dx.doi.org/10.1081/PDE-200050080.

[90] J. O'REILLY.*Observers for linear systems*, Mathematics in Science and Engineering, Academic Press Inc., Orlando, FL, 1983, vol. 170.

[91] J. ORTEGA, L. ROSIER, T. TAKAHASHI.*On the motion of a rigid body immersed in a bidimensional incompressible perfect fluid*, in "Ann. Inst. H. Poincaré Anal. Non Linéaire", 2007, vol. 24, n^{o} 1, p. 139–165, http://dx.doi.org/10.1016/j.anihpc.2005.12.004.

[92] K. RAMDANI, M. TUCSNAK, G. WEISS.*Recovering the initial state of an infinite-dimensional system using observers*, in "Automatica", 2010, vol. 46, n^{o} 10, p. 1616-1625.

[93] J.-P. RAYMOND.*Feedback stabilization of a fluid-structure model*, in "SIAM J. Control Optim.", 2010, vol. 48, n^{o} 8, p. 5398–5443, http://dx.doi.org/10.1137/080744761.

[94] J. SAN MARTÍN, J.-F. SCHEID, L. SMARANDA.*A modified Lagrange-Galerkin method for a fluid-rigid system with discontinuous density*, in "Numer. Math.", 2012, vol. 122, n^{o} 2, p. 341–382, http://dx.doi.org/10.1007/s00211-012-0460-1.

[95] J. SAN MARTÍN, J.-F. SCHEID, L. SMARANDA.*The Lagrange-Galerkin method for fluid-structure interaction problems*, in "Boundary Value Problems.", 2013, p. 213–246.

[96] J. SAN MARTÍN, J.-F. SCHEID, T. TAKAHASHI, M. TUCSNAK.*Convergence of the Lagrange-Galerkin method for the equations modelling the motion of a fluid-rigid system*, in "SIAM J. Numer. Anal.", 2005, vol. 43, n^{o} 4, p. 1536–1571 (electronic), http://dx.doi.org/10.1137/S0036142903438161.

[97] J. SAN MARTÍN, J.-F. SCHEID, T. TAKAHASHI, M. TUCSNAK.*An initial and boundary value problem modeling of fish-like swimming*, in "Arch. Ration. Mech. Anal.", 2008, vol. 188, n^{o} 3, p. 429–455, http://dx.doi.org/10.1007/s00205-007-0092-2.

[98] J. SAN MARTÍN, L. SMARANDA, T. TAKAHASHI.*Convergence of a finite element/ALE method for the Stokes equations in a domain depending on time*, in "J. Comput. Appl. Math.", 2009, vol. 230, n^{o} 2, p. 521–545, http://dx.doi.org/10.1016/j.cam.2008.12.021.

[99] J. SAN MARTÍN, V. STAROVOITOV, M. TUCSNAK.*Global weak solutions for the two-dimensional motion of several rigid bodies in an incompressible viscous fluid*, in "Arch. Ration. Mech. Anal.", 2002, vol. 161, n^{o} 2, p. 113–147, http://dx.doi.org/10.1007/s002050100172.

[100] D. SERRE.*Chute libre d'un solide dans un fluide visqueux incompressible. Existence*, in "Japan J. Appl. Math.", 1987, vol. 4, n^{o} 1, p. 99–110, http://dx.doi.org/10.1007/BF03167757.

[101] A. L. SILVESTRE.*On the self-propelled motion of a rigid body in a viscous liquid and on the attainability of steady symmetric self-propelled motions*, in "J. Math. Fluid Mech.", 2002, vol. 4, n^{o} 4, p. 285–326, http://dx.doi.org/10.1007/PL00012524.

[102] A. L. SILVESTRE.*Steady solutions with finite kinetic energy for a perturbed Navier-Stokes system in* $\mathbb{R}^3$, in "J. Differential Equations", 2009, vol. 247, n^{o} 7, p. 2124–2139, http://dx.doi.org/10.1016/j.jde.2009.07.003.

[103] P. STEFANOV, G. UHLMANN.*Thermoacoustic tomography with variable sound speed*, in "Inverse Problems", 2009, vol. 25, n^{o} 7, 16, 075011.

[104] T. TAKAHASHI.*Analysis of strong solutions for the equations modeling the motion of a rigid-fluid system in a bounded domain*, in "Adv. Differential Equations", 2003, vol. 8, n^{o} 12, p. 1499–1532.

[105] T. TAKAHASHI, M. TUCSNAK.*Global strong solutions for the two-dimensional motion of an infinite cylinder in a viscous fluid*, in "J. Math. Fluid Mech.", 2004, vol. 6, n^{o} 1, p. 53–77, http://dx.doi.org/10.1007/s00021-003-0083-4.

[106] H. TRINH, T. FERNANDO.*Functional observers for dynamical systems*, Lecture Notes in Control and Information Sciences, Springer, Berlin, 2012, vol. 420.

[107] J. L. VÁZQUEZ, E. ZUAZUA.*Large time behavior for a simplified 1D model of fluid-solid interaction*, in "Comm. Partial Differential Equations", 2003, vol. 28, n^{o} 9-10, p. 1705–1738, http://dx.doi.org/10.1081/PDE-120024530.

[108] H. F. WEINBERGER.*On the steady fall of a body in a Navier-Stokes fluid*, in "Partial differential equations (Proc. Sympos. Pure Math., Vol. XXIII, Univ. California, Berkeley, Calif., 1971)", Providence, R. I., Amer. Math. Soc., 1973, p. 421–439.

Team TONUS

TOkamaks and NUmerical Simulations

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
Nancy - Grand Est

THEME
Earth, Environmental and Energy Sciences

Table of contents

Team TONUS

Creation of the Team: 2012 January 01

Keywords:

Computer Science and Digital Science:

6. - Modeling, simulation and control
6.1. - Mathematical Modeling
6.1.1. - Continuous Modeling (PDE, ODE)
6.1.4. - Multiscale modeling
6.1.5. - Multiphysics modeling
6.2. - Scientific Computing, Numerical Analysis & Optimization
6.2.1. - Numerical analysis of PDE and ODE
6.2.7. - High performance computing
6.3.4. - Model reduction
7.1. - Parallel and distributed algorithms
7.11. - Performance evaluation

Other Research Topics and Application Domains:

1.1.10. - Mathematical biology
4.2.2. - Fusion
5.2.3. - Aviation
6.1.1. - Software engineering

1. Members

Research Scientists

Emmanuel Franck [Inria, Researcher]
Sever Hirstoaga [Inria, Researcher]

Faculty Members

Philippe Helluy [Team leader, Univ. Strasbourg, Professor, HDR]
Michaël Gutnic [Univ. Strasbourg, Associate Professor]
Michel Mehrenberger [Univ. Strasbourg, Associate Professor, HDR]
Laurent Navoret [Univ. Strasbourg, Associate Professor]
Christophe Steiner [Univ. Strasbourg, Associate Professor, until Aug 2016]

Technical Staff

Matthieu Boileau [CNRS]

PhD Students

Nicolas Bouzat [Inria]
Ksander Ejjaaouani [Inria, from october 2016]
Pierre Gerhard [Univ. Strasbourg]
Michel Massaro [Univ. Strasbourg, until Aug 2016]
Thi Trang Nhung Pham [Univ. Strasbourg, until Aug 2016]
Bruno Weber [Univ. Strasbourg]
Conrad Hillairet [Univ. Strasbourg, from November 2016]

Post-Doctoral Fellows

David Coulette [Univ. Strasbourg, from March 2016]
Malcolm Roberts [Univ. Strasbourg, until Aug 2016]
Laura Mendoza [Univ. Strasbourg, from November 2016]

Administrative Assistant

Céline Simon [Inria]

2. Overall Objectives

2.1. Overall Objectives

TONUS started in January 2014. It is a team of the Inria Nancy-Grand Est center. It is located in the mathematics institute (IRMA) of the university of Strasbourg.

The International Thermonuclear Experimental Reactor (ITER) is a large-scale scientific experiment that aims to demonstrate that it is possible to produce energy from fusion, by confining a very hot hydrogen plasma inside a toroidal chamber, called tokamak. In addition to physics and technology research, tokamak design also requires mathematical modeling and numerical simulations on supercomputers.

The objective of the TONUS project is to deal with such mathematical and computing issues. We are mainly interested in kinetic and gyrokinetic simulations of collisionless plasmas. In the TONUS project-team we are working on the development of new numerical methods devoted to such simulations. We investigate several classical plasma models, study new reduced models and new numerical schemes adapted to these models. We implement our methods in two software projects: Selalib [0] and SCHNAPS [0] adapted to new computer architectures. We intend to run challenging simulations on high performance computers with thousands of nodes.

We have strong relations with the CEA-IRFM team and participate to the development of their gyrokinetic simulation software GYSELA. We are involved in two Inria Project Labs, respectively devoted to tokamak mathematical modeling and high performance computing on future exascale super-computers. We also collaborate with a small company in Strasbourg specialized in numerical software for applied electromagnetics.

Finally, our subjects of interest are at the interaction between mathematics, computer science, High Performance Computing, physics and practical applications.

3. Research Program

3.1. Kinetic models for plasmas

The fundamental model for plasma physics is the coupled Vlasov-Maxwell kinetic model: the Vlasov equation describes the distribution function of particles (ions and electrons), while the Maxwell equations describe the electromagnetic field. In some applications, it may be necessary to take into account relativistic particles, which lead to consider the relativistic Vlasov equation, but generally, tokamak plasmas are supposed to be non relativistic. The distribution function of particles depends on seven variables (three for space, three for velocity and one for time), which yields a huge amount of computations.

To these equations we must add several types of source terms and boundary conditions for representing the walls of the tokamak, the applied electromagnetic field that confines the plasma, fuel injection, collision effects, etc.

Tokamak plasmas possess particular features, which require developing specialized theoretical and numerical tools.

[0] http://selalib.gforge.inria.fr/
[0] http://schnaps.gforge.inria.fr

Because the magnetic field is strong, the particle trajectories have a very fast rotation around the magnetic field lines. A full resolution would require prohibitive amount of calculations. It is then necessary to develop models where the cyclotron frequency tends to infinity in order to obtain tractable calculations. The resulting model is called a gyrokinetic model. It allows us to reduce the dimensionality of the problem. Such models are implemented in GYSELA and Selalib. Those models require averaging of the acting fields during a rotation period along the trajectories of the particles. This averaging is called the gyroaverage and requires specific discretizations.

The tokamak and its magnetics fields present a very particular geometry. Some authors have proposed to return to the intrinsic geometrical versions of the Vlasov-Maxwell system in order to build better gyrokinetic models and adapted numerical schemes. This implies the use of sophisticated tools of differential geometry: differential forms, symplectic manifolds, and Hamiltonian geometry.

In addition to theoretical modeling tools, it is necessary to develop numerical schemes adapted to kinetic and gyrokinetic models. Three kinds of methods are studied in TONUS: Particle-In-Cell (PIC) methods, semi-Lagrangian and fully Eulerian approaches.

3.1.1. Gyrokinetic models: theory and approximation

In most phenomena where oscillations are present, we can establish a three-model hierarchy: (i) the model parameterized by the oscillation period, (ii) the limit model and (iii) the two-scale model, possibly with its corrector. In a context where one wishes to simulate such a phenomenon where the oscillation period is small and where the oscillation amplitude is not small, it is important to have numerical methods based on an approximation of the Two-Scale model. If the oscillation period varies significantly over the domain of simulation, it is important to have numerical methods that approximate properly and effectively the model parameterized by the oscillation period and the Two-Scale model. Implemented Two-Scale Numerical Methods (for instance by Frénod et al. [20]) are based on the numerical approximation of the Two-Scale model. These are called of order 0. A Two-Scale Numerical Method is called of order 1 if it incorporates information from the corrector and from the equation of which this corrector is a solution. If the oscillation period varies between very small values and values of order 1, it is necessary to have new types of numerical schemes (Two-Scale Asymptotic Preserving Schemes of order 1 or TSAPS) with the property of being able to preserve the asymptotics between the model parameterized by the oscillation period and the Two-Scale model with its corrector. A first work in this direction has been initiated by Crouseilles et al. [18].

3.1.2. Semi-Lagrangian schemes

The Strasbourg team has a long and recognized experience in numerical methods of Vlasov-type equations. We are specialized in both particle and phase space solvers for the Vlasov equation: Particle-in-Cell (PIC) methods and semi-Lagrangian methods. We also have a longstanding collaboration with the CEA of Cadarache for the development of the GYSELA software for gyrokinetic tokamak plasmas.

The Vlasov and the gyrokinetic models are partial differential equations that express the transport of the distribution function in the phase space. In the original Vlasov case, the phase space is the six-dimension position-velocity space. For the gyrokinetic model, the phase space is five-dimensional because we consider only the parallel velocity in the direction of the magnetic field and the gyrokinetic angular velocity instead of three velocity components.

A few years ago, Eric Sonnendrücker and his collaborators introduced a new family of methods for solving transport equations in the phase space. This family of methods are the semi-Lagrangian methods. The principle of these methods is to solve the equation on a grid of the phase space. The grid points are transported with the flow of the transport equation for a time step and interpolated back periodically onto the initial grid. The method is then a mix of particle Lagrangian methods and Eulerian methods. The characteristics can be solved forward or backward in time leading to the Forward Semi-Lagrangian (FSL) or Backward Semi-Lagrangian (BSL) schemes. Conservative schemes based on this idea can be developed and are called Conservative Semi-Lagrangian (CSL).

GYSELA is a 5D full gyrokinetic code based on a classical backward semi-Lagrangian scheme (BSL) [27] for the simulation of core turbulence that has been developed at CEA Cadarache in collaboration with our team [21]. Although GYSELA was carefully developed to be conservative at lowest order, it is not exactly conservative, which might be an issue when the simulation is under-resolved, which always happens in turbulence simulations due to the formation of vortices which roll up.

3.1.3. PIC methods

Historically PIC methods have been very popular for solving the Vlasov equations. They allow solving the equations in the phase space at a relatively low cost. The main disadvantage of the method is that, due to its random aspect, it produces an important numerical noise that has to be controlled in some way, for instance by regularizations of the particles, or by divergence correction techniques in the Maxwell solver. We have a longstanding experience in PIC methods and we started implement them in Selalib. An important aspect is to adapt the method to new multicore computers. See the work by Crestetto and Helluy [17].

3.2. Reduced kinetic models for plasmas

As already said, kinetic plasmas computer simulations are very intensive, because of the gyrokinetic turbulence. In some situations, it is possible to make assumptions on the shape of the distribution function that simplify the model. We obtain in this way a family of fluid or reduced models.

Assuming that the distribution function has a Maxwellian shape, for instance, we obtain the MagnetoHydroDynamic (MHD) model. It is physically valid only in some parts of the tokamak (at the edges for instance). The fluid model is generally obtained from the hypothesis that the collisions between particles are strong. Fine collision models are mainly investigated by other partners of the IPL (Inria Project Lab) FRATRES. In our approach we do not assume that the collisions are strong, but rather try to adapt the representation of the distribution function according to its shape, keeping the kinetic effects. The reduction is not necessarily a consequence of collisional effects. Indeed, even without collisions, the plasma may still relax to an equilibrium state over sufficiently long time scales (Landau damping effect). Recently, a team at the Plasma Physics Institut (IPP) in Garching has carried out a statistical analysis of the 5D distribution functions obtained from gyrokinetic tokamak simulations [22]. They discovered that the fluctuations are much higher in the space directions than in the velocity directions (see Figure 1).

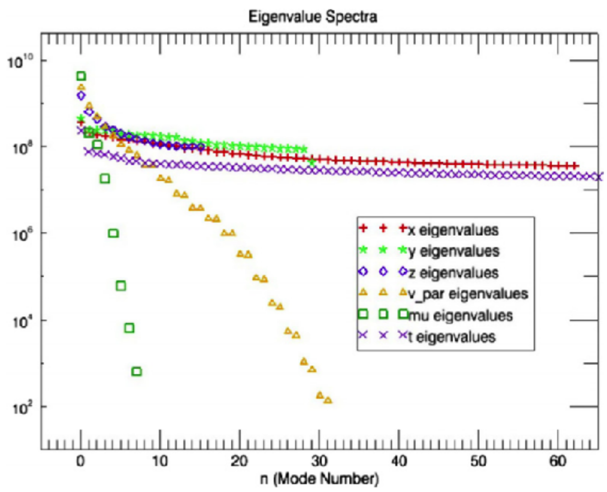

Figure 1. Space and velocity fluctuations spectra (from [22])

This indicates that the approximation of the distribution function could require fewer data while still achieving a good representation, even in the collisionless regime.

Our approach is different from the fluid approximation. In what follows we call this the "reduced model" approach. A reduced model is a model where the explicit dependency on the velocity variable is removed. In a more mathematical way, we consider that in some regions of the plasma, it is possible to exhibit a (preferably small) set of parameters α that allows us to describe the main properties of the plasma with a generalized "Maxwellian" M. Then

$$f(x,v,t) = M(\alpha(x,t),v).$$

In this case it is sufficient to solve for $\alpha(x,t)$. Generally, the vector α is solution of a first order hyperbolic system.

Several approaches are possible: waterbag approximations, velocity space transforms, *etc.*

3.2.1. Velocity space transformations

An experiment made in the 60's [25] exhibits in a spectacular way the reversible nature of the Vlasov equations. When two perturbations are applied to a plasma at different times, at first the plasma seems to damp and reach an equilibrium. But the information of the perturbations is still here and "hidden" in the high frequency microscopic oscillations of the distribution function. At a later time a resonance occurs and the plasma produces an echo. The time at which the echo occurs can be computed (see Villani [0], page 74). The fine mathematical study of this phenomenon allowed C. Villani and C. Mouhot to prove their famous result on the rigorous nonlinear Landau damping [26].

More practically, this experiment and its theoretical framework show that it is interesting to represent the distribution function by an expansion on an orthonormal basis of oscillating functions in the velocity variables. This representation allows a better control of the energy transfer between the low frequencies and the high frequencies in the velocity direction, and thus provides more relevant numerical methods. This kind of approach is studied for instance by Eliasson in [19] with the Fourier expansion.

In long time scales, filamentation phenomena result in high frequency oscillations in velocity space that numerical schemes cannot resolve. For stability purposes, most numerical schemes contain dissipation mechanisms that may affect the precision of the finest oscillations that can be resolved.

3.2.2. Adaptive modeling

Another trend in scientific computing is to optimize the computation time through adaptive modeling. This approach consists in applying the more efficient model locally, in the computational domain, according to an error indicator. In tokamak simulations, this kind of approach could be very efficient, if we are able to choose locally the best intermediate kinetic-fluid model as the computation runs. This field of research is very promising. It requires developing a clever hierarchy of models, rigorous error indicators, versatile software architecture, and algorithms adapted to new multicore computers.

3.2.3. Numerical schemes

As previously indicated, an efficient method for solving the reduced models is the Discontinuous Galerkin (DG) approach. It is possible to make it of arbitrary order. It requires limiters when it is applied to nonlinear PDEs occurring for instance in fluid mechanics. But the reduced models that we intent to write are essentially linear. The nonlinearity is concentrated in a few coupling source terms.

In addition, this method, when written in a special set of variables, called the entropy variables, has nice properties concerning the entropy dissipation of the model. It opens the door to constructing numerical schemes with good conservation properties and no entropy dissipation, as already used for other systems of PDEs [28], [16], [24], [23].

[0] Landau damping. CEMRACS 2010 lectures. http://smai.emath.fr/cemracs/cemracs10/PROJ/Villani-lectures.pdf

3.3. Electromagnetic solvers

A precise resolution of the electromagnetic fields is essential for proper plasma simulation. Thus it is important to use efficient solvers for the Maxwell systems and its asymptotics: Poisson equation and magnetostatics.

The proper coupling of the electromagnetic solver with the Vlasov solver is also crucial for ensuring conservation properties and stability of the simulation.

Finally plasma physics implies very different time scales. It is thus very important to develop implicit Maxwell solvers and Asymptotic Preserving (AP) schemes in order to obtain good behavior on long time scales.

3.3.1. Coupling

The coupling of the Maxwell equations to the Vlasov solver requires some precautions. The most important is to control the charge conservation errors, which are related to the divergence conditions on the electric and magnetic fields. We will generally use divergence correction tools for hyperbolic systems presented for instance in [15] (and included references).

3.3.2. Implicit solvers

As already pointed out, in a tokamak, the plasma presents several different space and time scales. It is not possible in practice to solve the initial Vlasov-Maxwell model. It is first necessary to establish asymptotic models by letting some parameters (such as the Larmor frequency or the speed of light) tend to infinity. This is the case for the electromagnetic solver and this requires implementing implicit time solvers in order to efficiently capture the stationary state, the solution of the magnetic induction equation or the Poisson equation.

4. Application Domains

4.1. Controlled fusion and ITER

The search for alternative energy sources is a major issue for the future. Among others, controlled thermonuclear fusion in a hot hydrogen plasma is a promising possibility. The principle is to confine the plasma in a toroidal chamber, called a tokamak, and to attain the necessary temperatures to sustain nuclear fusion reactions. The International Thermonuclear Experimental Reactor (ITER) is a tokamak being constructed in Cadarache, France. This was the result of a joint decision by an international consortium made of the European Union, Canada, USA, Japan, Russia, South Korea, India and China. ITER is a huge project. As of today, the budget is estimated at 20 billion euros. The first plasma shot is planned for 2020 and the first deuterium-tritium operation for 2027.

Many technical and conceptual difficulties have to be overcome before the actual exploitation of fusion energy. Consequently, much research has been carried out around magnetically confined fusion. Among these studies, it is important to carry out computer simulations of the burning plasma. Thus, mathematicians and computer scientists are also needed in the design of ITER. The reliability and the precision of numerical simulations allow a better understanding of the physical phenomena and thus would lead to better designs. TONUS's main involvement is in such research.

The required temperatures to attain fusion are very high, of the order of a hundred million degrees. Thus it is imperative to prevent the plasma from touching the tokamak inner walls. This confinement is obtained thanks to intense magnetic fields. The magnetic field is created by poloidal coils, which generate the toroidal component of the field. The toroidal plasma current also induces a poloidal component of the magnetic field that twists the magnetic field lines. The twisting is very important for the stability of the plasma. The idea goes back to research by Tamm and Sakharov, two Russian physicists, in the 1950's. Other devices are essential for the proper operation of the tokamak: divertor for collecting the escaping particles, microwave heating for reaching higher temperatures, fuel injector for sustaining the fusion reactions, toroidal coils for controlling instabilities, etc.

4.2. Other applications

The software and numerical methods that we develop can also be applied to other fields of physics or of engineering.

- For instance, we have a collaboration with the company AxesSim in Strasbourg for the development of efficient Discontinuous Galerkin (DG) solvers on hybrid computers. The applications is electromagnetic simulations for the conception of antenna, electronic devices or aircraft electromagnetic compatibility.
- The acoustic conception of large rooms requires huge numerical simulations. It is not always possible to solve the full wave equation and many reduced acoustic models have been developed. A popular model consists in considering "acoustic" particles moving at the speed of sound. The resulting Partial Differential Equation (PDE) is very similar to the Vlasov equation. The same modeling is used in radiation theory. We have started to work on the reduction of the acoustic particles model and realized that our reduction approach perfectly applies to this situation. A new PhD with CEREMA (Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement) has started in October 2015 (thesis of Pierre Gerhard). The objective is to investigate the model reduction and to implement the resulting acoustic model in our DG solver.

5. New Software and Platforms

5.1. SCHNAPS - KIRSCH

Participants: Emmanuel Franck, Pierre Gerhard, Philippe Helluy, Michel Massaro, Malcolm Roberts, David Coulette, Laura Mendoza, Bruno Weber.

SCHNAPS: Solveur pour les lois de Conservation Hyperboliques Non-linéaires Appliqué aux PlasmaS
SCIENTIFIC DESCRIPTION

The future computers will be made of a collection of thousands of interconnected multicore processors. Globally, it appears as a classical distributed memory MIMD machine. But at a lower level, each of the multicore processors is itself made of a shared memory MIMD unit (a few classical CPU cores) and a SIMD unit (a GPU or Xeon Phi). When designing new algorithms, it is important to adapt them to this kind of architecture. Practically, we use the MPI library for managing the coarse grain parallelism, while the OpenCL library efficiently operate the fine grain parallelism.

We have invested for several years until now into scientific computing on GPUs, using the open standard OpenCL (Open Computing Language). We were recently awarded a prize in the international AMD OpenCL innovation challenge thanks to an OpenCL two-dimensional Vlasov-Maxwell solver that fully runs on a GPU. OpenCL is a very interesting tool because it is an open standard now available on almost all brands of multicore processors and GPUs. The same parallel program can run on a GPU or a multicore processor without modification. OpenCL programs are quite complicated to construct. For instance it is difficult to distribute efficiently the computation or memory operations on the different available accelerators. StarPU http://starpu.gforge.inria.fr/ is a runtime system developed at Inria Bordeaux that simplifies the distribution of tasks on heterogeneous compute units. We have started to use this software tool in SCHNAPS.

Because of the envisaged applications, which may be either academic or commercial, it is necessary to conceive a modular framework. The kernel of the library is made of generic parallel algorithms for solving conservation laws. The parallelism can be both fine-grained (oriented towards GPUs and multicore processors) and coarse-grained (oriented towards GPU clusters). The separate modules allow managing the meshes and some specific applications. With our partner AxesSim, we also develop a C++ specific version of SCHNAPS for electromagnetic applications.
Since the middle of the year a specific version of SCHNAPS (called KIRSCH for Kinetic Representation of SChnaps) has been developed to handle Lattice Boltzmann schemes for MHD and fluid simulations.

FUNCTIONAL DESCRIPTION

SCHNAPS and KIRSCH are a generic Discontinuous Galerkin solver and an implicit Lattice Boltzmann solver, written in C, based on the OpenCL, MPI and StarPU frameworks.

- Partner: AxesSim
- Contact: Philippe Helluy
- URL: http://schnaps.gforge.inria.fr/

5.2. Selalib

Participants: Sever Adrian Hirstoaga, Michel Mehrenberger, Pierre Navaro, Laurent Navoret, Thi Trang Nhung Pham, Christophe Steiner.

KEYWORDS: Plasma physics - Semi-Lagrangian method - PIC - Parallel computing - Plasma turbulence

SCIENTIFIC DESCRIPTION

The objective of the Selalib project (SEmi-LAgrangian LIBrary) is to develop a well-designed, organized and documented library implementing several numerical methods for kinetic models of plasma physics. Its ultimate goal is to produce gyrokinetic simulations.

Another objective of the library is to provide to physicists easy-to-use gyrokinetic solvers, based on the semi-Lagrangian techniques developed by Eric Sonnendrücker and his collaborators in the past CALVI project. The new models and schemes from TONUS are also intended to be incorporated into Selalib.

FUNCTIONAL DESCRIPTION

Selalib is a collection of modules conceived to aid in the development of plasma physics simulations, particularly in the study of turbulence in fusion plasmas. Selalib offers basic capabilities from general and mathematical utilities and modules to aid in parallelization, up to pre-packaged simulations.

- Partners: Max Planck Institute - Garching - IRMA, Université de Strasbourg - IRMAR, Université Rennes 1 - LJLL, Université Paris 6
- Contact: Michel Mehrenberger
- URL: http://selalib.gforge.inria.fr/

5.3. Django

Participants: Emmanuel Franck [correspondent], Boniface Nkonga, Ahmed Ratnani.

- Scientific description:
  The JOREK code is one of the most important MHD codes in Europe. This code written 15 years ago allows to simulate the MHD instabilities which appear in the Tokamak. Using this code the physicists have obtained some important results. However to run larger and more complex test cases it is necessary to extend the numerical methods used.
  In 2014, the DJANGO code has been created, the aim of this code is twofold: have a numerical library to implement, test and validate new numerical methods for MHD, fluid mechanics and Electromagnetic equations in the finite element context and prepare the future new JOREK code. This code is a 2D-3D code based on implicit time schemes and IsoGeometric (B-Splines, Bezier curves) for the spatial discretization.
- Functional description:
  DJANGO is a finite element implicit solver written in Fortran 2008 with a Basic MPI framework.
- Authors:
  Ahmed Ratnani (Max Planck Institut of Plasma Physic, Garching, Germany), Boniface Nkonga (University of Nice and Inria Sophia-Antipolis, France), Emmanuel Franck (Inria Nancy Grand Est, TONUS Team)

- Contributors:
  Mustafa Gaja, Jalal Lakhlili, Matthias Hoelzl and Eric Sonnendrücker (Max Planck Institut of Plasma Physic, Garching, Germany), Ayoub Iaagoubi (ADT Inria Nice), Hervé Guillard (University of Nice and Inria Sophia-Antipolis, France), Virginie Grandgirard, Guillaume Latu (CEA Cadarache, France)
- Year 2016:
  Between the years 2015 and 2016 the code has been partially rewritten using Fortran 2008 to prepare the implementation of new methods (compatible finite element spaces, 3D B-Splines meshes). The different models, hyperbolic, parabolic and elliptic introduced in the previous version of the code have been rewritten and validated. Actually, we will begin to introduce the Maxwell equations for the coupling with kinetic equations and the nonlinear fluid models (first step for the MHD simulations). A large effort of optimization and parallelization in the matrices assembly has been made and new preconditioning for elliptic models has been introduced.
  - Partners: Max Planck Institute - Garching - IRMA, Université de Strasbourg - Inria Nice Sofia- Antipolis
  - Contact: Emmanuel Franck

6. New Results

6.1. Time scheme for finite elements code for fluids models

Participants: Emmanuel Franck, Philippe Helluy, David Coulette, Ahmed Ratnani, Eric Sonnendrücker.

The finite element code JOREK use currently a classical implicit solver for reduced MHD model coupled with a block Jacobi preconditioning. For the future full MHD code we propose to change the solver in time to reduce the memory consumption and improve the robustness. During this year two directions have been followed. The first one is based on the classical physics-based preconditioning proposed by L. Chacon. Firstly, we have generalized this method by rewriting the preconditioning as a splitting scheme which separates the advection terms and the acoustic part and by generalizing the splitting algorithm. We obtain different solutions with different advantages. These different splitting schemes have been tested on simplified models and are currently tested on the Euler equations. The second direction is to use a relaxation scheme which allows to rewrite a nonlinear system as a linear hyperbolic system (larger that the previous one) and a nonlinear local source term. Using a splitting scheme we obtain a very simple method where in the first step we solve independent linear transport problems and in a second step we have some nonlinear projections. With a good parallelism and good solver for the transport subproblems the algorithm is very efficient compared to the classical one.

6.2. Preconditioning for elliptic solvers

Participants: Emmanuel Franck, Mariarosa Mazza, Ahmed Ratnani, Eric Sonnendrücker, Stefano Serra-Capizzano.

The different algorithms to discretize in time the MHD or to design preconditioning use solvers for a lot of elliptic operators like Laplacian. For high order finite elements like B-Splines the classical multi-grid methods are not very efficient. Indeed the number of iterations to converge increases strongly when the polynomial order increases. Using a theory called GLT, proposed by S. Serra-Capizzano, we have implemented and validated a smoother for multi-grid, able to obtain the convergence quasi independent of the polynomial degree. This method is also efficient as a preconditioning for mass matrices. We obtain at the end, very robust solvers for these simple problems and allows to perform the time algorithm for fluid models. The next step is to extend this method for more complex problems like vectorial elliptic problems.

6.3. Implicit Lattice Boltzmann scheme for fluid models

Participants: Emmanuel Franck, Philippe Helluy, David Coulette, Conrad Hillairet.

Many systems of conservation laws can be written under a lattice-kinetic form. A lattice-kinetic model is made of a finite set of transport equations coupled through a relaxation source term. Such representation is very useful:

- easy stability analysis, possibility to add second order terms in a natural way;
- can be solved by a splitting strategy;
- easy-to-implement implicit schemes, avoiding CFL constraint;
- high parallelism.

We have started to work on such approaches for solving the MHD equation inside a tokamak (postdoc of David Coulette). We have programmed a generic parallel lattice-kinetic solver in Kirsch, using the StarPU runtime. It presents a very good parallel efficiency. We have also started studying more theoretical aspects: stability of kinetic models, higher order time-integration, viscous terms modeling.

6.4. Hybrid computing

Participants: Philippe Helluy, Nhung Pham, Michel Massaro, Pierre Gerhard, David Coulette, Laura Mendoza, Conrad Hillairet.

In order to harness hybrid computers architecture, we have developed software and algorithms that are well adapted to CPU/GPU computing. For instance we have applied a task-graph approach for computing electromagnetic waves (https://hal.archives-ouvertes.fr/hal-01134222). We have also used an OpenCL-based GPU version of schnaps for computing a drift-kinetic plasma model (Nhung Pham's PhD). Recently, we have also developed a new implementation of the Discontinuous Galerkin solver into schnaps. We now use the StarPU runtime (http://starpu.gforge.inria.fr) for addressing automatically CPUs or GPUs available on the computational node. This development has been applied to the MHD equations (thesis of Michel Massaro). The new development will now be applied to kinetic acoustic simulations (Pierre Gerhard's PhD), gyrokinetic plasma simulations (Laura Mendoza's Postdoc) and implicit MHD simulations (Conrad Hillairet's PhD).

6.5. DG scheme for Drift-Kinetic equation

Participants: Laurent Navoret [correspondent], Philippe Helluy, Nhung Pham.

Using the discontinuous Galerkin solver of Schnaps, we have implemented a numerical scheme for the drift-kinetic model (in a cylinder geometry). The equation is written as an hyperbolic system after reduction in velocity (using spectral finite element). The code is parallelized on a multi-CPU or GPU architecture using OpenCL instructions. To solve the quasineutral equation (for the electric potential), the elliptic solver (already present in Schnaps) has been extended to be used slice by slice (of the cylinder). We have started by validating the code on the 2D guiding-center model and the diocotron instability test-case: we observe that the geometry approximation of the computational domain has a major impact on the precision of the numerical simulations.

6.6. Quasi-neutrality equation in a polar mesh

Participants: Michel Mehrenberger, Philippe Helluy, Guillaume Latu, Nicolas Crouseilles, Christophe Steiner.

In the quasi-neutrality equation in GYSELA, we are now able to treat correctly the inner radius thanks to a simple trick by taking the inner radius $\frac{\Delta r}{2}$. We also continue working on the gyro-average approximation. The new Padé method depends on a parameter ε. When setting ε to a large value, the solution is very similar to the classical Padé one, while taking small value for ε leads to a solution very near to the one obtained using the interpolation method (which approximates better the exact operator, but which can however lead to unstable results as it does not damp high modes). We can then prevent the scheme from instability, by setting large ε, but not too large in order to be more accurate than the classical Padé approximation. Further study in GYSELA is under discussion.

6.7. PICSL: Particle in Cell and Semi-Lagrangian schemes for two species plasma simulations

Participants: Michel Mehrenberger [correspondent], Sever Hirstoaga, Joackim Bernier, Yann Barsamian.

We have worked at CEMRACS 2016 on an algorithm that handles both the Particle in Cell method and the Semi-Lagrangian method in the context of a $2D \times 2D$ to handle the different scales associated with the ions and the electrons in Vlasov-Poisson simulation. Using PIC methods for the electrons allows to use easily specific numerical methods for fast dynamic. Numerical results are in accordance with the dispersion relation.

6.8. TARGET: TArgeting Realistic GEometry in Tokamak code gysela

Participants: Michel Mehrenberger, Nicolas Bouzat, Guillaume Latu, Camilla Bressan, Virginie Grandgirard.

We have worked at CEMRACS2016 on a new variant for the interpolation method to handle both mesh singularity at the origin and non circular geometry. It is based on a non uniform number of points for each closed flux line (intersection of the flux surfaces with the poloidal plane), which are concentric circles in the case of the circular geometry. This strategy, following previous works on curvilinear geometry and hexagonal meshes, should allow to generalize the work in [14] to non circular tokamaks.

6.9. Field aligned interpolation for gyrokinetics

Participants: Michel Mehrenberger, Maurizio Ottaviani, Yaman Güçlü, Guillaume Latu, Eric Sonnendrücker.

A theoretical justification of the field align method is provided in the simplified context of constant advection on a 2D periodic domain: unconditional stability is proven, and error estimates are given which highlight the advantages of field-aligned interpolation. The same methodology is successfully applied to the solution of the gyrokinetic Vlasov equation, for which we present the ion temperature gradient (ITG) instability as a classical test-case: first we solve this in cylindrical geometry (screw-pinch), and next in toroidal geometry (circular Tokamak). A paper has been submitted [14].

6.10. High order implicit time splitting schemes for the BGK model

Participants: Michel Mehrenberger, Philippe Helluy, Laurent Navoret, David Coulette, Emmanuel Franck.

In the context of the Lattice Boltzmann or relaxation methods (6.1-6.3), it is interesting to obtain a very high order implicit splitting. For this, we have considered a time splitting discretization of the BGK model with 3 velocities. First and second order schemes are studied before using Strang splitting coupled with a Semi Lagrangian or a Cranck-Nicholson DG scheme. Using complex time steps and composition methods, we obtain 4th order time step, unconditionally stable for the discrete BGK models. These results could be used with the Lattice Boltzmann method, the relaxation method and also the kinetic model.

6.11. Particle-In-Cell simulations for Vlasov-Poisson equations

Participants: Sever Hirstoaga, Yann Barsamian.

In the work [3], we implement in Selalib an efficient, regarding the memory access, Particle-In-Cell method which enables simulations with a large number of particles. Numerical results for classical one-dimensional Landau damping and two-dimensional Kelvin-Helmholtz test cases are exposed. The implementation also relies on a standard hybrid MPI/OpenMP parallelization. Code performance is assessed by the observed speedup and attained memory bandwidth. A convergence result is also illustrated by comparing the numerical solution of a four-dimensional Vlasov-Poisson system against the one for the guiding center model.

Then, we continued to optimize the code by analyzing different data structures for the particles (structure of arrays vs. arrays of structure) and for the grid fields (using space-filling curves like Morton, Hilbert etc.) with the aim of improving the cache reuse. In addition, we added the functionality of vectorization from the compiler and we obtained significant gain by testing the different data structures. We thus achieved to run PIC simulations processing 65 million particles/second on an Intel Haswell architecture, without hyper-threading. The hybrid parallelization through OpenMP/MPI gave satisfactory strong and weak scaling up to 8192 cores on GENCI's supercomputer Curie.

6.12. Kinetic modeling and simulation of edge tokamak plasmas and plasma-wall interactions

Participants: Sever Hirstoaga, David Coulette, Giovanni Manfredi.

We performed a full parallelization (over species and using 4D domain decomposition) of the 1D3V Multi-species Vlasov-Poisson finite-volumes code. The 4D code was then used to perform, by means of parametric studies, an analysis of the structure of the multi-scale boundary layer (the so-called Debye sheath and various pre-sheaths) for a magnetized-plasma in contact with an absorbing wall. This study allowed us to show, notably, that when the strong confining magnetic field is close to grazing incidence with respect to the absorbing surface, the boundary layer extends further into the plasma and as a result the magnitude of the electric field is lessened.
A second study was devoted to the dynamics of the propagation of the so-called "ELMs" (Edge-Localized-Modes) at the edge of Tokamak devices. The $1D1V$ collisionless model used in previous studies was extended by coupling a $1D1V$ kinetic model for the fast parallel propagation of the plasma disturbance along magnetic field lines with a fluid model in the directions perpendicular to the magnetic field. The coupling occurs by means of collision operators allowing for energy transfer between the parallel and perpendicular degrees of freedom. The initial asymptotic preserving scheme was extended to allow for adaptive time-stepping due to the introduction of the fluid transport equation. Using simulation results for various realistic collision rates we showed that collisional isotropization of the electronic population have a significant impact on the heat flux impacting the devices wall. The results were presented to the magnetic fusion community at the EPS conference in Leuven [9].

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

We are involved in a common project with the company AxesSim in Strasbourg. The objective is to help for the development of a commercial software devoted to the numerical simulation of electromagnetic phenomena. The applications are directed towards antenna design and electromagnetic compatibility. This project was partly supported by DGA through "RAPID" (*régime d'appui à l'innovation duale*) funds. The CIFRE PhD of Thomas Strub is part of this project. Another CIFRE PhD has started in AxesSim on the same kind of topic in March 2015 (Bruno Weber). The new project is devoted to the use of a runtime system in order to optimize DG solvers applied to electromagnetism. The resulting software will be used for the numerical simulation of connected devices for clothes or medicine. The project is supported by the "Banque Public d'Investissement" (BPI) and coordinated by the Thales company.

8. Partnerships and Cooperations

8.1. Regional Initiatives

The thesis of Pierre Gerhard devoted to numerical simulation of room acoustics is supported by the Alsace region. It is a joint project with CEREMA (*Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement*) in Strasbourg.

8.2. National Initiatives

8.2.1. ANR

ANR project PEPPSI (models for edge plasma physic in Tokamak) in *Programme Blanc* SIMI 9, started in 2013. Participants, G. Manfredi (coordinator), S. Hirstoaga, D. Coulette.
Participants: Giovanni Manfredi [coordinator], Sever Adrian Hirstoaga.

8.2.2. IPL FRATRES

The TONUS project belongs to the IPL FRATRES (models and numerical methods for Tokamak). The annual meeting has been organized in Strasbourg by Emmanuel Franck and Philippe Helluy.

8.2.3. IPL C2S@exa

The TONUS and HIEPACS projects have obtained the financial support for the PhD thesis of Nicolas Bouzat thanks to the IPL C2S@exa (computational sciences at exascale). Nicolas Bouzat works at CEA Cadarache and is supervised locally by Guillaume Latu; the PhD advisors are Michel Mehrenberger and Jean Roman.

8.2.4. Competitivity clusters

GENCI projet : "*Simulation numérique des plasmas par des méthodes semi-lagrangiennes et PIC adaptées*". 450 000 scalar computing hours on CURIE_standard (January 2016-January 2017); coordinator: Michel Mehrenberger
Participants: Sever Adrian Hirstoaga, Guillaume Latu, Michel Mehrenberger, Thi Nhung Pham, Christophe Steiner, Yann Barzamian.

8.3. European Initiatives

8.3.1. FP7 & H2020 Projects

8.3.1.1. EUROfusion 2015-2017

Eurofusion Enabling Research Project ER15-IPP01 (1/2015-12/2017) "Verification and development of new algorithms for gyrokinetic codes" (Principal Investigator: Eric Sonnendrücker, Max-Planck Institute for Plasma Physics, Garching).
Participants: Philippe Helluy, Sever Adrian Hirstoaga, Michel Mehrenberger.

Eurofusion Enabling Research Project ER15-IPP05 (1/2015-12/2017) "Global non-linear MHD modeling in toroidal geometry of disruptions, edge localized modes, and techniques for their mitigation and suppression" (Principal Investigator: Matthias Hoelzl, Max-Planck Institute for Plasma Physics, Garching).
Participant: Emmanuel Franck.

8.4. International Initiatives

8.4.1. Inria International Partners

8.4.1.1. Informal International Partners

Michel Mehrenberger collaborates with Bedros Afeyan (Pleasanton, USA) on KEEN wave simulations.

Emmanuel Franck collaborates with E. Sonnendruecker (IPP Garching) and S. Serra Capizzano (University of Como, Italy) on preconditioning for IGA methods.

8.4.2. Participation In other International Programs

Participants: Conrad Hillairet, David Coulette, Emmanuel Franck, Philippe Helluy [local coordinator].

ANR/SPPEXA "EXAMAG" is a joint French-German-Japanese project. Its goal is to develop efficient parallel MHD solvers for future exascale architectures. With our partners, we plan to apply highly parallelized and hybrid solvers for plasma physics. One of our objectives is to develop Lattice-Boltzmann MHD solvers based on high-order implicit Discontinous Galerkin methods, using SCHNAPS and runtime systems such as StarPU.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Journal

9.1.1.1. Member of the editorial boards

Philippe Helluy is member of the editorial board of IJFV http://ijfv.org/

9.1.1.2. Reviewer - Reviewing activities

Emmanuel Franck has been reviewer for

- Communications in computational physics
- Methods and Algorithms for Scientific Computing
- Methods for Partial Differential equations

Philippe Helluy has been reviewer for

- Math. Review
- International Journal for Numerical Methods in Fluids
- Computers and fluids
- M2AN
- ESAIM Proceedings
- PIER Journal

Sever Adrian Hirstoaga has been reviewer for

- Journal of Fixed Point Theory and Applications
- MathSciNet/Mathematical Reviews

Michel Mehrenberger has been reviewer for

- SISC
- Electronic Journal of Qualitative Theory of Differential Equations (EJQTDE)
- Mathematical Methods in the Applied Sciences
- Journal Of Computational Physics
- Computer Physics Communications
- Computational and Applied Mathematics
- Zeitschrift fuer Angewandte Mathematik und Physik

David Coulette has been reviewer for

- Journal of Plasma Physics - Cambridge University Press

9.1.2. Invited Talks

Emmanuel Franck was invited at

- Minisymposium Fusion, Canum 2016, Obernai
- Workshop Jorek, Nice, France
- Seminar of numerical analysis, Rennes university, France

Emmanuel Franck has participated as speaker at

ECCOMAS 2016, Greece

Workshop ABPDE 2016, Lille, France

IGA and free mesh methods, La Jolla, USA

Philippe Helluy was invited at:

Oberwolfach au workshop (Hyperbolic Techniques for Phase Dynamics)

Sever Adrian Hirstoaga was invited at

17th SIAM Conference on Parallel Processing for Scientific Computing, 12-15 April 2016, Paris.

PASC (Platform for Advanced Scientific Computing), 8-10 June 2016, Lausanne.

NumKin, October 2016, Strasbourg

Michel Mehrenberger was invited at

ECCOMAS Congress 2016 , 5-10 june 2016 Crete Island, Greece.

Conference - Stability of non-conservative systems 4th-7th July 2016, University of Valenciennes, France.

Collaborative Research Center (CRC) seminar, Karlsruhe Institute of Technology (KIT), 28 april 2016.

Seminar, "Modellistica Differenziale Numerica", Dipartimento di Matematica - Sapienza Universita di Roma, 19 april 2016.

Seminar, "Applications des mathématiques", ENS Rennes, 2 mars 2016.

Laurent Navoret was invited at

Seminar. Laboratoire Jean Kuntzmann Grenoble

Workshop: Kinetic theory : from equations to models - Imperial College, Londres

Laurent Navoret has participated as speaker at

Congres Hyp2016, Aachen, Germany

David Coulette was invited at

14eme congress of French Physics Society and IAP Plasma Workshop, Nancy France

European Physical Society - 43rd conference on Plasma Physics, Leuven - Belgium

9.1.3. Scientific Expertise

Philippe Helluy, expertises for:

ANR

9.1.4. Research Administration

Philippe Helluy is the head of the "Modélisation et Contrôle" research team at IRMA Strasbourg.

Michel Mehrenberger is in the IREM ("Institut de recherche sur l'enseignement des mathématiques") team "Modélisation" for the year 2016-2017.

Philippe Helluy and Sever Hirstoaga have participated in a jury for an assistant professor position.

Michaël Gutnic is member of the National Commitee for Scientific Research (from september 2012 to august 2016).

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Licence : Laurent Navoret, Nonlinear optimisation (108h eq. TD)

Licence : Laurent Navoret, Integration (34h eq. TD)

Licence : Philippe Helluy, scientific computing (70h eq. TD)

Licence : Philippe Helluy, statistic (50h eq. TD)

Licence : Philippe Helluy, basic mathematics (20h eq. TD)

Licence : Michel Mehrenberger, Scientific computing (65 h eq. TD)

Licence : Michel Mehrenberger, nonlinear optimization (18 h eq. TD)

Licence : Michel Mehrenberger, mathematics for chemistry (56h eq. TD)

Licence: Michaël Gutnic, Mathematics for biology, (84h eq. TD)

Licence: Michaël Gutnic, Statistic for biology, (65h eq. TD)

Master 1: Laurent Navoret, Python (19h eq. TD)

Master 1: Philippe Helluy, operational research (50h eq. TD)

Master 1: Michaël Gutnic, probability and statistic, (30h eq. TD)

Master 2 (Agrégation) : Laurent Navoret, scientific computing (50h eq. TD)

Master 2 (Cellar physic) : Laurent Navoret, Basics in maths (24h eq. TD)

Master 2 (Agrégation) : Michel Mehrenberger, scientific computing (28h eq. TD)

Master 2: Philippe Helluy, hyperbolic systems (30h eq. TD)

Master 2: Sever Hirstoaga "two-scales convergence" (24h eq. TD)

9.2.2. Supervision

PhD defended (december 2016): Thi Trang Nhung Pham, "Méthodes numériques pour Vlasov", Advisors: Philippe Helluy, Laurent Navoret.

PhD defended (december 2016): Michel Massaro, "Méthodes numériques pour les plasmas sur architectures multicœurs", Advisor: Philippe Helluy.

PhD in progress: Pierre Gerhard, "Résolution des modèles cinétiques. Application à l'acoustique du bâtiment.", October 2015, Advisors: Philippe Helluy, Laurent Navoret.

PhD in progress: Bruno Weber, "Optimisation de code Galerkin Discontinu sur ordinateur hybride. Application à la simulation numérique en électromagnétisme", March 2015, Advisor: Philippe Helluy.

PhD in progress: Nicolas Bouzat, "Fine grain algorithms and deployment methods for exascale codes", October 2015, Advisors: Michel Mehrenberger, Jean Roman, Guillaume Latu.

PhD in progress: Mustafa Gaja, "Compatible finite element method and preconditioning", December 2015, Advisors: E. Sonnendruecker (IPP, germany), A. Ratnani (IPP), E. Franck

PhD in progress: Conrad Hillairet, "Implicit Boltzmann scheme and Task Parallelization for MHD simulations", November 2016, Advisors: Philippe Helluy, E. Franck

PhD in progress: Ksander Ejjaouani, "Conception of a programmation model, application to gyrokinetic simulations", October 2015, Advisors: Michel Mehrenberger, Julien Bigot, Olivier Aumage.

9.2.3. Juries

Philippe Helluy:

PhD defense of Rémi Chauvin (Toulouse)

PhD defense of Eric Madaule (Nancy)

PhD defense of Juan Manuel Martinez Caamano (Strasbourg)

PHD defense of Thibault Gasc (CEA Paris)

PHD defense of Nicolas Deymier (Toulouse)

Habilitation defense of Virginie Grandgirard (CEA cadarache)

Michel Mehrenberger:

PhD defense of Florian Delage (Strasbourg)

10. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] M. MASSARO.*Numerical methods for plasmas on massively parallel architectures*, Université de Strasbourg, IRMA UMR 7501, December 2016, https://tel.archives-ouvertes.fr/tel-01410049.

Articles in International Peer-Reviewed Journal

[2] C. BUET, B. DESPRÉS, E. FRANCK, T. LEROY.*Proof of uniform convergence for a cell-centered AP discretization of the hyperbolic heat equation on general meshes*, in "Mathematics of Computation", September 2016, https://hal.archives-ouvertes.fr/hal-00956573.

[3] F. CASAS, N. CROUSEILLES, E. FAOU, M. MEHRENBERGER.*High-order Hamiltonian splitting for Vlasov-Poisson equations*, in "Numerische Mathematik", 2016, https://hal.inria.fr/hal-01206164.

[4] E. CHACON-GOLCHER, S. A. HIRSTOAGA, M. LUTZ.*Optimization of Particle-In-Cell simulations for Vlasov-Poisson system with strong magnetic field*, in "ESAIM: Proceedings and Surveys", 2016, vol. 53, p. 177-190 [*DOI :* 10.1051/PROC/201653011], https://hal.archives-ouvertes.fr/hal-01231444.

[5] D. COULETTE, S. A. HIRSTOAGA, G. MANFREDI.*Effect of collisional temperature isotropisation on ELM parallel transport in a tokamak scrape-off layer*, in "Plasma Physics and Controlled Fusion", July 2016, vol. 58, n^{o} 8, 085004, https://hal.inria.fr/hal-01399230.

[6] D. COULETTE, G. MANFREDI.*Kinetic simulations of the Chodura and Debye sheaths for magnetic fields with grazing incidence*, in "Plasma Physics and Controlled Fusion", 2016, vol. 58, n^{o} 2, 25008 [*DOI :* 10.1088/0741-3335/58/2/025008], https://hal.archives-ouvertes.fr/hal-01402204.

[7] E. FRANCK, L. S. MENDOZA.*Finite volume scheme with local high order discretization of Hydrostatic equilibrium for Euler equations with external forces*, in "Journal of Scientific Computing", October 2016, https://hal.inria.fr/hal-01114437.

[8] A. HAMIAZ, M. MEHRENBERGER, H. SELLAMA, E. SONNENDRÜCKER.*The semi-Lagrangian method on curvilinear grids*, in "Communications in Applied and Industrial Mathematics", 2016, https://hal.archives-ouvertes.fr/hal-01213366.

[9] P. HELLUY, O. HURISSE, E. LE COUPANEC.*Verification of a two-phase flow code based on an homogeneous model*, in "International Journal on Finite Volumes", November 2016, vol. 13, https://hal.archives-ouvertes.fr/hal-01396200.

Conferences without Proceedings

[10] D. COULETTE, G. MANFREDI, S. A. HIRSTOAGA.*Kinetic modeling and numerical simulation of plasma-wall interactions in magnetic fusion devices*, in "43rd European Physical Society Conference on Plasma Physics", Leuwen , Belgium, July 2016, https://hal.archives-ouvertes.fr/hal-01402210.

Scientific Books (or Scientific Book chapters)

[11] P. HELLUY, T. STRUB, M. MASSARO, M. ROBERTS.*Asynchronous OpenCL/MPI numerical simulations of conservation laws*, in "Software for Exascale Computing - SPPEXA 2013-2015", H.-J. BUNGARTZ, P. NEUMANN, W. E. NAGEL (editors), Springer International Publishing, 2016, p. 547–565 [*DOI :* 10.1007/978-3-319-40528-5_25], https://hal.archives-ouvertes.fr/hal-01134222.

Other Publications

[12] C. COURTÈS, E. FRANCK, P. HELLUY, H. OBERLIN.*Study of Physics-Based preconditioning with High-order Galerkin discretization for hyperbolic wave problems*, November 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01401547.

[13] P. HELLUY.*Stability analysis of an implicit lattice Boltzmann scheme*, 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01403759.

[14] G. LATU, M. MEHRENBERGER, Y. GÜÇLÜ, M. OTTAVIANI, E. SONNENDRÜCKER.*Field-aligned interpolation for semi-Lagrangian gyrokinetic simulations*, May 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01315889.

References in notes

[15] C. ALTMANN, T. BELAT, M. GUTNIC, P. HELLUY, H. MATHIS, E. SONNENDRÜCKER, W. ANGULO, J.-M. HÉRARD.*A local time-stepping Discontinuous Galerkin algorithm for the MHD system*, in "Modélisation et Simulation de Fluides Complexes - CEMRACS 2008", Marseille, France, July 2009 [*DOI :* 10.1051/PROC/2009038], https://hal.inria.fr/inria-00594611.

[16] T. BARTH.*On the role of involutions in the discontinous Galerkin discretization of Maxwell and magnetohydrodynamic systems*, in "IMA Vol. Math. Appl.", 2006, vol. 142, p. 69–88.

[17] A. CRESTETTO, P. HELLUY.*Resolution of the Vlasov-Maxwell system by PIC Discontinuous Galerkin method on GPU with OpenCL*, in "CEMRACS'11", France, EDP Sciences, 2011, vol. 38, p. 257–274 [*DOI :* 10.1051/PROC/201238014], https://hal.archives-ouvertes.fr/hal-00731021.

[18] N. CROUSEILLES, E. FRÉNOD, S. A. HIRSTOAGA, A. MOUTON.*Two-Scale Macro-Micro decomposition of the Vlasov equation with a strong magnetic field*, in "Mathematical Models and Methods in Applied Sciences", 2013, vol. 23, n^{o} 08, p. 1527–1559 [*DOI :* 10.1142/S0218202513500152.], https://hal.archives-ouvertes.fr/hal-00638617.

[19] B. ELIASSON.*Outflow boundary conditions for the Fourier transformed one-dimensional Vlasov-Poisson system*, in "J. Sci. Comput.", 2001, vol. 1, p. 1–28.

[20] E. FRENOD, F. SALVARANI, E. SONNENDRÜCKER.*Long time simulation of a beam in a periodic focusing channel via a two-scale PIC-method*, in "Mathematical Models and Methods in Applied Sciences", 2009, vol. 19, n^{o} 2, p. 175-197, ACM 82D10 35B27 76X05, http://hal.archives-ouvertes.fr/hal-00180700/en/.

[21] V. GRANDGIRARD, M. BRUNETTI, P. BERTRAND, N. BESSE, X. GARBET, P. GHENDRIH, G. MANFREDI, Y. SARAZIN, O. SAUTER, E. SONNENDRÜCKER, J. VACLAVIK, L. VILLARD.*A drift-kinetic Semi-Lagrangian 4D Vlasov code for ion turbulence simulation*, in "J. of Comput. Phys.", 2006, vol. 217, 395.

[22] D. HATCH, D. DEL-CASTILLO-NEGRETE, P. TERRY.*Analysis and compression of six-dimensional gyrokinetic datasets using higher order singular value decomposition*, in "Journal of Computational Physics", 2012, vol. 231, p. 4234–4256.

[23] C. HAUCK, C.-D. LEVERMORE.*Convex Duality and Entropy-Based Moment Closures: Characterizing Degenerate Densities*, in "SIAM J. Control Optim.", 2008, vol. 47, p. 1977–2015.

[24] C.-D. LEVERMORE.*Entropy-based moment closures for kinetic equations*, in "Transport Theory Statist. Phys.", 1997, vol. 26, n^{o} 4-5, p. 591–606.

[25] J. MALMBERG, C. WHARTON.*Collisionless damping of electrostatic plasma waves*, in "Phys. Rev. Lett.", 1964, vol. 13, n^{o} 6, p. 184–186.

[26] C. MOUHOT, C. VILLANI.*On Landau damping*, in "Acta Mathematica", 2011, vol. 207, p. 29-201.

[27] E. SONNENDRÜCKER, J.-R. ROCHE, P. BERTRAND, A. GHIZZO.*The semi-Lagrangian method for the numerical resolution of the Vlasov equation*, in "J. Comput. Phys.", 1999, vol. 149, n^{o} 2, p. 201–220.

[28] E. TADMOR.*Entropy conservative finite element schemes*, in "Numerical methods for Compressible Flows, Finite Difference Element and Volume Techniques", T. E. TEZDUYAR, T. J. R. HUGHES (editors), Proc. Winter Annual Meeting, Amer. Soc. Mech. Eng, AMD- Vol. 78, 1986, 149.

Project-Team VEGAS

Effective Geometric Algorithms for Surfaces and Visibility

IN COLLABORATION WITH: Laboratoire lorrain de recherche en informatique et ses applications (LORIA)

IN PARTNERSHIP WITH:
CNRS

Université de Lorraine

RESEARCH CENTER
Nancy - Grand Est

THEME
Algorithmics, Computer Algebra and Cryptology

Table of contents

Project-Team VEGAS

Creation of the Project-Team: 2005 August 01, end of the Project-Team: 2016 December 31

Keywords:

Computer Science and Digital Science:

5.10.1. - Design
6.2.3. - Probabilistic methods
7.2. - Discrete mathematics, combinatorics
7.5. - Geometry, Topology
7.6. - Computer Algebra

Other Research Topics and Application Domains:

5. - Industry of the future

1. Members

Research Scientists

Sylvain Lazard [Team leader, Inria, Senior Researcher, HDR]
Olivier Devillers [Inria, Senior Researcher, HDR]
Guillaume Moroz [Inria, Researcher]
Marc Pouget [Inria, Researcher]
Monique Teillaud [Inria, Senior Researcher, HDR]

Faculty Member

Laurent Dupont [Univ. Lorraine, Associate Professor]

Technical Staff

Eric Biagioli [Inria, since Nov. 2016]

PhD Students

Sény Diatta [Univ. Lorraine Mobility program since Nov. 2016]
Charles Duménil [Univ. Lorraine, since Oct. 2016]
Iordan Iordanov [Univ. Lorraine]

Post-Doctoral Fellow

Rémi Imbach [Inria, until Oct. 2016]

Visiting Scientist

Gert Vegter [Univ. Lorraine, May 2016]

Administrative Assistants

Laurence Benini [Inria, until Aug. 2016]
Laurence Félicité [Univ. Lorraine, until Mar. 2016]
Hélène Zganic [Inria, since Sept. 2016]
Virginie Priester [CNRS, since Apr. 2016]

Other

Louis Noizet [ENS Paris, Internship, from June 2016 until Aug. 2016]

2. Overall Objectives

2.1. Overall Objectives

The main scientific objective of the VEGAS research team is to *contribute to the development of an effective geometric computing* dedicated to *non-trivial geometric objects*. Included among its main tasks are the study and development of new algorithms for the manipulation of geometric objects, the experimentation of algorithms, the production of high-quality software, and the application of such algorithms and implementations to research domains that deal with a large amount of geometric data, notably solid modeling and computer graphics.

Computational geometry has traditionally treated linear objects like line segments and polygons in the plane, and point sets and polytopes in three-dimensional space, occasionally (and more recently) venturing into the world of non-linear curves such as circles and ellipses. The methodological experience and the know-how accumulated over the last thirty years have been enormous.

For many applications, particularly in the fields of computer graphics and solid modeling, it is necessary to manipulate more general objects such as curves and surfaces given in either implicit or parametric form. Typically such objects are handled by approximating them by simple objects such as triangles. This approach is extremely important and it has been used in almost all of the usable software existing in industry today. It does, however, have some disadvantages. Using a tessellated form in place of its exact geometry may introduce spurious numerical errors (the famous gap between the wing and the body of the aircraft), not to mention that thousands if not hundreds of thousands of triangles could be needed to adequately represent the object. Moreover, the curved objects that we consider are not necessarily everyday three-dimensional objects, but also abstract mathematical objects that are not linear, that may live in high-dimensional space, and whose geometry we do not control. For example, the set of lines in 3D (at the core of visibility issues) that are tangent to three polyhedra span a piecewise ruled quadratic surface, and the lines tangent to a sphere correspond, in projective five-dimensional space, to the intersection of two quadratic hypersurfaces.

Effectiveness is a key word of our research project. By requiring our algorithms to be effective, we imply that the algorithms should be *robust,efficient,* and *versatile*. By robust we mean algorithms that do not crash on degenerate inputs and always output topologically consistent data. By efficient we mean algorithms that run reasonably quickly on realistic data where performance is ascertained both experimentally and theoretically. Finally, by versatile we mean algorithms that work for classes of objects that are general enough to cover realistic situations and that account for the *exact geometry* of the objects, in particular when they are curved.

3. Application Domains

3.1. Computer Graphics

We are interested in the application of our work to virtual prototyping, which refers to the many steps required for the creation of a realistic virtual representation from a CAD/CAM model.

When designing an automobile, detailed physical mockups of the interior are built to study the design and evaluate human factors and ergonomic issues. These hand-made prototypes are costly, time consuming, and difficult to modify. To shorten the design cycle and improve interactivity and reliability, realistic rendering and immersive virtual reality provide an effective alternative. A virtual prototype can replace a physical mockup for the analysis of such design aspects as visibility of instruments and mirrors, reachability and accessibility, and aesthetics and appeal.

Virtual prototyping encompasses most of our work on effective geometric computing. In particular, our work on 3D visibility should have fruitful applications in this domain. As already explained, meshing objects of the scene along the main discontinuities of the visibility function can have a dramatic impact on the realism of the simulations.

3.2. Solid Modeling

Solid modeling, i.e., the computer representation and manipulation of 3D shapes, has historically developed somewhat in parallel to computational geometry. Both communities are concerned with geometric algorithms and deal with many of the same issues. But while the computational geometry community has been mathematically inclined and essentially concerned with linear objects, solid modeling has traditionally had closer ties to industry and has been more concerned with curved surfaces.

Clearly, there is considerable potential for interaction between the two fields. Standing somewhere in the middle, our project has a lot to offer. Among the geometric questions related to solid modeling that are of interest to us, let us mention: the description of geometric shapes, the representation of solids, the conversion between different representations, data structures for graphical rendering of models and robustness of geometric computations.

4. Highlights of the Year

4.1. Highlights of the Year

Inria signed a contract for the integration of ISOTOP within Maple.

The project-team VEGAS will terminate at the end of 2016. A new project-team GAMBLE (Geometric Algorithms and Models Beyond the Linear and Euclidean realm) is currently submitted. It intends to extend computational geometry to non-linear objects, non-Euclidean spaces and probabilistic complexities.

5. New Software and Platforms

5.1. ISOTOP

Topology and geometry of planar algebraic curves
KEYWORDS: Topology - Curve plotting - Geometric computing
Isotop is a Maple software for computing the topology of an algebraic plane curve, that is, for computing an arrangement of polylines isotopic to the input curve. This problem is a necessary key step for computing arrangements of algebraic curves and has also applications for curve plotting.

This software, registered at the APP in June 2011, has been developed since 2007 in collaboration with F. Rouillier from Inria Paris. The distributed version is based on the method described in [3], which presents several improvements over previous methods. In particular, our approach does not require generic position. This version is competitive with other implementations (such as ALCIX and INSULATE developed at MPII Saarbrücken, Germany and TOP developed at Santander Univ., Spain). It performs similarly for small-degree curves and performs significantly better for higher degrees, in particular when the curves are not in generic position.

We are currently working on an improved version integrating a new bivariate polynomial solver based on several of our recent results published in [11]. This version is not yet distributed.

Via the Inria ADT FastTrack funding, Eric Biagioli has joined the project in November 2016 for 6 months. He is porting the maple code to C code and enhancing the visualization. This work will prepare for a better diffusion of the software via a webserver and a transfert to Maplesoft with which Inria has signed a contract in April 2016.

- Contact: Sylvain Lazard & Marc Pouget
- URL: http://vegas.loria.fr/isotop/

5.2. SubdivisionSolver

KEYWORDS: Numerical solver - Polynomial or analytical systems

The software SubdivisionSolver solves square systems of analytic equations on a compact subset of a real space of any finite dimension. SubdivisionSolver is a numerical solver and as such it requires that the solutions in the subset are isolated and regular for the input system (i.e. the Jacobian must not vanish). SubdivisionSolver is a subdivision solver using interval arithmetic and multiprecision arithmetic to achieve certified results. If the arithmetic precision required to isolate solutions is known, it can be given as an input parameter of the process, otherwise the precision is increased on the fly. In particular, SubdivisionSolver can be interfaced with the Fast_Polynomial library (https://bil.inria.fr/en/software/view/2423/tab) to solve polynomial systems that are large in terms of degree, number of monomials and bit-size of coefficients.

The software is based on a classic branch and bound algorithm using interval arithmetic: an initial box is subdivided until its sub-boxes are certified to contain either no solution or a unique solution of the input system. Evaluation is performed with a centered evaluation at order two, and existence and uniqueness of solutions is verified thanks to the Krawczyk operator.

SubdivisionSolver uses two implementations of interval arithmetic: the C++ boost library that provides a fast arithmetic when double precision is enough, and otherwise the C mpfi library that allows to work in arbitrary precision. Considering the subdivision process as a breadth first search in a tree, the boost interval arithmetic is used as deeply as possible before a new subdivision process using higher precision arithmetic is performed on the remaining forest.

The software has been improved and a technical report published [28].

- Contact: Rémi Imbach
- URL: https://bil.inria.fr/fr/software/view/2605/tab

6. New Results

6.1. Non-linear Computational Geometry

Participants: Laurent Dupont, Rémi Imbach, Sylvain Lazard, Guillaume Moroz, Marc Pouget.

6.1.1. Numeric and Certified Algorithm for the Topology of the Projection of a Smooth Space Curve

Let a smooth real analytic curve embedded in $\mathbb{R}^3$ be defined as the solution of real analytic equations of the form $P(x, y, z) = Q(x, y, z) = 0$ or $P(x, y, z) = \frac{\partial P}{\partial z} = 0$. Our main objective is to describe its projection $\mathcal{C}$ onto the (x, y)-plane. In general, the curve $\mathcal{C}$ is not a regular submanifold of $\mathbb{R}^2$ and describing it requires to isolate the points of its singularity locus Σ.

In previous work, we have shown how to describe the set of singularities Σ of $\mathcal{C}$ as regular solutions of a so-called ball system suitable for a numerical subdivision solver. In our current work, the space curve is first enclosed in a set of boxes with a certified path-tracker to restrict the domain where the ball system is solved. Boxes around singular points are then computed such that the correct topology of the curve inside these boxes can be deduced from the intersections of the curve with their boundaries. The tracking of the space curve is then used to connect the smooth branches to the singular points. The subdivision of the plane induced by the curve is encoded as an extended planar combinatorial map allowing point location. This work is not already published but has been presented by R. Imbach at the Summer Workshop on Interval Methods (https://swim2016.sciencesconf.org/).

The technical report [28] describes the software SubdivisionSolver (see Section 5.2) used within this project.

6.1.2. A Fast Algorithm for Computing the Truncated Resultant

Let P and Q be two polynomials in $\mathbb{K}[x,y]$ with degree at most d, where $\mathbb{K}$ is a field. Denoting by $R \in \mathbb{K}[x]$ the resultant of P and Q with respect to y, we present an algorithm to compute $R \mod x^k$ in $\widetilde{O}(kd)$ arithmetic operations in $\mathbb{K}$, where the $\widetilde{O}$ notation indicates that we omit polylogarithmic factors. This is an improvement over state-of-the-art algorithms that require to compute R in $\widetilde{O}(d^3)$ operations before computing its first k coefficients [24].

This work was done in collaboration with Éric Schost (Waterloo University, Canda).

6.1.3. Quadric Arrangement in Classifying Rigid Motions of a 3D Digital Image

Rigid motions are fundamental operations in image processing. While bijective and isometric in $\mathbb{R}^3$, they lose these properties when digitized in $\mathbb{Z}^3$. To understand how the digitization of 3D rigid motions affects the topology and geometry of a chosen image patch, we classify the rigid motions according to their effect on the image patch. This classification can be described by an arrangement of hypersurfaces in the parameter space of 3D rigid motions of dimension six. However, its high dimensionality and the existence of degenerate cases make a direct application of classical techniques, such as cylindrical algebraic decomposition or critical point method, difficult. We show that this problem can be first reduced to computing sample points in an arrangement of quadrics in the 3D parameter space of rotations. Then we recover information about the three remaining parameters of translation. We implemented an ad-hoc variant of state-of-the-art algorithms and applied it to an image patch of cardinality 7. This leads to an arrangement of 81 quadrics and we recovered the classification in less than one hour on a machine equipped with 40 cores [25].

This work was done in collaboration with Kacper Pluta (LIGM - Laboratoire d'Informatique Gaspard-Monge), Yukiko Kenmochi (LIGM - Laboratoire d'Informatique Gaspard-Monge), Pascal Romon (LAMA - Laboratoire d'Analyse et de Mathématiques Appliquées).

6.1.4. Influence of the Trajectory Planning on the Accuracy of the Orthoglide 5-axis manipulator

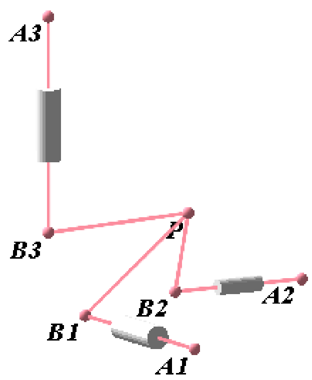

Figure 1. A configuration of the orthoglide manipulator has three orthogonal prismatic joints.

Usually, the accuracy of parallel manipulators depends on the architecture of the robot, the design parameters, the trajectory planning and the location of the path in the workspace. This paper reports the influence of static and dynamic parameters in computing the error in the pose associated with the trajectory planning made and analyzed with the Orthoglide 5-axis (Figure 1). An error model is proposed based on the joint parameters (velocity and acceleration) and experimental data coming from the Orthoglide 5-axis. Newton and Gröbner based elimination methods are used to project the joint error in the workspace to check the accuracy/error in the Cartesian space. For the analysis, five similar trajectories with different locations inside the workspace are defined using fifth order polynomial equation for the trajectory planning. It is shown that the accuracy of the robot depends on the location of the path as well as the starting and the ending posture of the manipulator due to the acceleration parameters [23].

This work was done in collaboration with Ranjan Jha (IRCCyN - Institut de Recherche en Communications et en Cybernétique de Nantes), Damien Chablat (IRCCyN - Institut de Recherche en Communications et en Cybernétique de Nantes), Fabrice Rouillier (Inria).

6.1.5. Solving Bivariate Systems and Topology of Plane Algebraic Curves

In the context of our algorithm Isotop for computing the topology of plane algebraic curves (see Section 5.1), we work on the problem of solving a system of two bivariate polynomials. We are interested in certified numerical approximations or, more precisely, isolating boxes of the solutions. But we are also interested in computing, as intermediate symbolic objects, a Rational Univariate Representation (RUR) that is, roughly speaking, a univariate polynomial and two rational functions that map the roots of the univariate polynomial to the two coordinates of the solutions of the system. RURs are relevant symbolic objects because they allow to the transformation of many queries on the system into queries on univariate polynomials. However, such representations require the computation of a separating form for the system, that is a linear combination of the variables that takes different values when evaluated at the distinct solutions of the system.

We published this year [11] results showing that, given two polynomials of degree at most d with integer coefficients of bitsize at most τ, (i) a separating form, (ii) the associated RUR, and (iii) isolating boxes of the solutions can be computed in, respectively, $\widetilde{O}_B(d^5 + d^5\tau)$, bit operations in the worst case, where $\widetilde{O}$ refers to the complexity where polylogarithmic factors are omitted and O_B refers to the bit complexity. Furthermore, we also presented probabilistic Las Vegas variants of problems (i) and (ii), which have expected bit complexity $\widetilde{O}_B(d^5 + d^4\tau)$. We also showed that these complexities are "morally" optimal in the sense of that improving them would essentially require to improve bounds on several other fundamental problems (on resultants and roots isolation of univariate polynomials) that have hold for decades. These progresses are substential since, when we started woriking on these problems, their best know complexities were in $\widetilde{O}_B(d^{12} + d^{10}\tau^2)$ (2009).

This work was done in collaboration with Yacine Bouzidi (Inria Lille), Michael Sagraloff (MPII Sarrebruken, Germany) and Fabrice Rouillier (Inria Rocquencourt).

6.1.6. Reflection through Quadric Mirror Surfaces

We addressed the problem of finding the reflection point on quadric mirror surfaces, especially ellipsoid, paraboloid or hyperboloid of two sheets, of a light ray emanating from a 3D point source P_1 and going through another 3D point P_2, the camera center of projection. We previously proposed a new algorithm for this problem, using a characterization of the reflection point as the tangential intersection point between the mirror and an ellipsoid with foci P_1 and P_2. The computation of this tangential intersection point is based on our algorithm for the computation of the intersection of quadrics [5], [32]. Unfortunately, our new algorithm is not yet efficient in practice. This year, we made several improvements on this algorithm. First, we decreased from 11 to 4 the degree of a critical polynomial that we need to solve and whose solutions induce the coefficients in some other polynomials appearing later in the computations. Second, we implemented Descartes' algorithm for isolating the real roots of univariate polynomials in the case where the coefficients belong to extensions of $\mathbb{Q}$ generated by at most two square roots. Furthermore, we are currently implementing the generalization of that algorithm when the coefficients belong to extensions of $\mathbb{Q}$ generated by one root of an arbitrary polynomial. We are also interested by extensions decomposable in extensions of degree 2. These undergoing improvements should allow us to compute more directly the wanted reflection point, thus avoiding problematic approximations and making the overall algorithm tractable.

6.2. Non-Euclidean Computational Geometry

Participants: Iordan Iordanov, Monique Teillaud, Gert Vegter.

6.2.1. Closed Flat Orbifolds

The work on Delaunay triangulations of flat d-dimensional orbifolds, started several years ago in the Geometrica project team in Sophia Antipolis, was finalized this year [13].

We give a definition of the Delaunay triangulation of a point set in a closed Euclidean d-manifold, i.e. a compact quotient space of the Euclidean space for a discrete group of isometries (a so-called Bieberbach group or crystallographic group). We describe a geometric criterion to check whether a partition of the manifold actually forms a triangulation (which subsumes that it is a simplicial complex). We provide an incremental algorithm to compute the Delaunay triangulation of the manifold defined by a given set of input points, if it exists. Otherwise, the algorithm returns the Delaunay triangulation of a finite-sheeted covering space of the manifold. The algorithm has optimal randomized worst-case time and space complexity. It extends to closed Euclidean orbifolds. To the best of our knowledge, this is the first general result on this topic.

6.2.2. Closed Orientable Hyperbolic Surfaces

Motivated by applications in various fields, some packages to compute periodic Delaunay triangulations in the 2D and 3D Euclidean spaces have been introduced in the CGAL library and have attracted a number of users. To the best of our knowledge, no software is available to compute periodic triangulations in a hyperbolic space, though they are also used in diverse fields, such as physics, solid modeling, cosmological models, neuromathematics.

This would be a natural extension: 2D Euclidean periodic triangulations can be seen as triangulations of the two-dimensional (flat) torus of genus one; similarly, periodic triangulations in the hyperbolic plane can be seen as triangulations of hyperbolic surfaces. A closed orientable hyperbolic surface is the quotient of the hyperbolic plane under the action of a Fuchsian group only containing hyperbolic translations. Intuition is challenged there, in particular because such groups are non-Abelian in general.

We have obtained some theoretical results on Delaunay triangulations of general closed orientable hyperbolic surfaces, and we have investigated algorithms in the specific case of the Bolza surface, a hyperbolic surface with the simplest possible topology, as it is homeomorphic to a genus-two torus [20]. We are now studying more practical aspects and we propose a first implementation of an incremental construction of Delaunay triangulations of the Bolza surface [30].

6.3. Probabilistic Analysis of Geometric Data Structures and Algorithms

Participants: Olivier Devillers, Louis Noizet.

6.3.1. Stretch Factor of Long Paths in a Planar Poisson-Delaunay Triangulation

Let $X := X_n \cup \{(0,0),(1,0)\}$, where X_n is a planar Poisson point process of intensity n. We provide a first non-trivial lower bound for the distance between the expected length of the shortest path between $(0,0)$ and $(1,0)$ in the Delaunay triangulation associated with X when the intensity of X_n goes to infinity. Experimental values indicate that the correct value is about 1.04. We also prove that the expected number of Delaunay edges crossed by the line segment $[(0,0),(1,0)]$ is equivalent to $2.16\sqrt{n}$ and that the expected length of a particular path converges to 1.18 giving an upper bound on the stretch factor [26].

This work was done in collaboration with Nicolas Chenavier (Université Littoral Côte d'Opale).

6.3.2. *Walking in a Planar Poisson-Delaunay Triangulation: Shortcuts in the Voronoi Path*

Let X_n be a planar Poisson point process of intensity n. We give a new proof that the expected length of the Voronoi path between $(0,0)$ and $(1,0)$ in the Delaunay triangulation associated with X_n is $\frac{4}{\pi} \simeq 1.27$ when n goes to infinity; and we also prove that the variance of this length is $O(1/\sqrt{n})$. We investigate the length of possible shortcuts in this path, and defined a shortened Voronoi path whose expected length can be expressed as an integral that is numerically evaluated to $\simeq 1.16$. The shortened Voronoi path has the property to be *locally defined*; and is shorter than the previously known locally defined path in Delaunay triangulation such as the upper path whose expected length is $35/3\pi^2 \simeq 1.18$ [27].

6.3.3. *Expected Length of the Voronoi Path in a High Dimensional Poisson-Delaunay Triangulation*

Let X_n be a d dimensional Poisson point process of intensity n. We prove that the expected length of the Voronoi path between two points at distance 1 in the Delaunay triangulation associated with X_n is $\sqrt{\frac{2d}{\pi}} + O(d^{-\frac{1}{2}})$ for all $n \in \mathbb{N}$ and $d \to \infty$. In any dimension, we provide a precise interval containing the exact value, in 3D the expected length is between 1.4977 and 1.50007 [31].

This work was done in collaboration with Pedro Machado Manhães De Castro (Centro de Informática da Universidade Federal de Pernambuco).

6.4. Classical Computational Geometry and Graph Drawing

Participants: Olivier Devillers, Sylvain Lazard.

6.4.1. *Monotone Simultaneous Path Embeddings in* $\mathbb{R}^d$

We study the following problem: Given k paths that share the same vertex set, is there a simultaneous geometric embedding of these paths such that each individual drawing is monotone in some direction? We prove that for any dimension $d \geq 2$, there is a set of $d+1$ paths that does not admit a monotone simultaneous geometric embedding [21].

This work was done in collaboration with David Bremner (U. New Brunswick), Marc Glisse (Inria Datashape), Giuseppe Liotta (U. Perugia), Tamara Mchedlidze (Karlsruhe Institute for Technology), Sue Whitesides (U. Victoria), and Stephen Wismath (U. Lethbridge).

6.4.2. *Analysis of Farthest Point Sampling for Approximating Geodesics in a Graph*

A standard way to approximate the distance between two vertices p and q in a graph is to compute a shortest path from p to q that goes through one of k sources, which are well-chosen vertices. Precomputing the distance between each of the k sources to all vertices yields an efficient computation of approximate distances between any two vertices. One standard method for choosing k sources is the so-called *Farthest Point Sampling* (FPS), which starts with a random vertex as the first source, and iteratively selects the farthest vertex from the already selected sources.

We analyzed the stretch factor $\mathcal{F}_{\text{FPS}}$ of approximate geodesics computed using FPS, which is the maximum, over all pairs of distinct vertices, of their approximated distance over their geodesic distance in the graph. We showed that $\mathcal{F}_{\text{FPS}}$ can be bounded in terms of the minimal value $\mathcal{F}^*$ of the stretch factor obtained using an optimal placement of k sources as $\mathcal{F}_{\text{FPS}} \leq 2r_e^2\mathcal{F}^* + 2r_e^2 + 8r_e + 1$, where r_e is the length ratio of longest edge over the shortest edge in the graph. We further showed that the factor r_e is not an artefact of the analysis by providing a class of graphs for which $\mathcal{F}_{\text{FPS}} \geq \frac{1}{2}r_e\mathcal{F}^*$ [18].

This work was done in collaboration with Pegah Kamousi (Université Libre de Bruxelles), Anil Maheshwari (Carleton University), and Stefanie Wuhrer (Inria Grenoble Rhône-Alpes).

6.4.3. Recognizing Shrinkable Complexes is NP-complete

We say that a simplicial complex is shrinkable if there exists a sequence of admissible edge contractions that reduces the complex to a single vertex. We prove that it is NP-complete to decide whether a (three-dimensional) simplicial complex is shrinkable. Along the way, we describe examples of contractible complexes which are not shrinkable [10].

This work was done in collaboration with Dominique Attali (CNRS, Grenoble) and Marc Glisse (Inria Datashape).

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

A two years licence and cooperation agreement was signed on April 1st, 2016 between WATERLOO MAPLE INC., Ontario, Canada (represented by Laurent Bernardin, its Executive Vice President Products and Solutions) and Inria. On the Inria side, this contract involves the teams VEGAS and OURAGAN (Paris), and it is coordinated by Fabrice Rouillier (OURAGAN).

F. Rouillier and VEGAS are the developers of the ISOTOP software for the computation of topology of curves. One objective of the contract is to transfer a version of ISOTOP to WATERLOO MAPLE INC.

8. Partnerships and Cooperations

8.1. Regional Initiatives

We organized, with IECL, a «journée Charles Hermite» about geometry and probability. A regular working group on the topic was started in november.

8.2. National Initiatives

8.2.1. ANR PRESAGE

The white ANR grant PRESAGE brings together computational geometers (from the VEGAS and GEOMETRICA projects of Inria) and probabilistic geometers (from Universities of Rouen, Orléans and Poitiers) to tackle new probabilistic geometry problems arising from the design and analysis of geometric algorithms and data structures. We focus on properties of discrete structures induced by random continuous geometric objects.

The project, with a total budget of 400kE, started on Dec. 31st, 2011 and ended in March 2016. It is coordinated by Xavier Goaoc who moved from the Vegas team to Marne-la-Vallée university in 2013.

Project website: https://members.loria.fr/GMoroz/ANR-Presage/.

8.2.2. ANR SingCAST

The objective of the young-researcher ANR grant SingCAST is to intertwine further symbolic/numeric approaches to compute efficiently solution sets of polynomial systems with topological and geometrical guarantees in singular cases. We focus on two applications: the visualization of algebraic curves and surfaces and the mechanical design of robots.

After identifying classes of problems with restricted types of singularities, we plan to develop dedicated symbolic-numerical methods that take advantage of the structure of the associated polynomial systems that cannot be handled by purely symbolic or numerical methods. Thus we plan to extend the class of manipulators that can be analyzed, and the class of algebraic curves and surfaces that can be visualized with certification.

This is a 3.5 years project, with a total budget of 100kE, that started on March 1st 2014, coordinated by Guillaume Moroz.

The project funded the postdoc position of Rémi Imbach from November 2014 until October 2016. We organized two workshops in 2016 with the OPTI team in Nantes, on certified surface continuation.

Project website: https://project.inria.fr/singcast/.

8.3. International Initiatives

8.3.1. Participation in Other International Programs

8.3.1.1. Nancy Emerging Associate Team Astonishing

The objectives of the *ASsociate Team On Non-ISH euclIdeaN Geometry* is to study various structures and algorithms in non-Euclidean spaces, from a computational geometry viewpoint. Proposing algorithms operating in such spaces requires a prior deep study of the mathematical properties of the objects considered, which raises new fundamental and difficult questions that we want to tackle.

A key characteristic of the project is its interdisciplinarity: it gathers approaches, knowledge, and tools in mathematics and computer science. A mathematical study of the considered objects will be performed, together with the design of algorithms when applicable. Algorithms will be analyzed both in theory and in practice after prototype implementations. In the long term, implementations should be improved whenever it makes sense to target longer-term integrations into CGAL, in order to disseminate our results to end-users.

The partners are the Johann Bernouilli Institute of Mathematics and Computer Science of University of Groningen, the Mathematics Research Unit of University of Luxembourg, and the Talgo team of École Normale Supérieure. The project is coordinated by Monique Teillaud and supported by Inria Nancy - Grand Est.

Project website: https://members.loria.fr/Monique.Teillaud/collab/Astonishing/.

8.4. International Research Visitors

8.4.1. Visits of International Scientists

8.4.1.1. Invited Professor

Gert Vegter, Professor at Univerity of Groningen, was awarded an invited professor position by University of Lorraine and spent one month in the group in May. He is coordinating the NEAT Astonishing on the Dutch side.

8.4.1.2. PhD Visitor

Sény Diatta, Senegalese PhD student co-advised by Guillaume Moroz, Daouda Niang Diatta (Ziguinchor) and Marie-Françoise Roy (Rennes), obtained a bourse Eiffel from Campus France, which includes a salary for 10 months to visit LORIA.

8.4.2. Visits to International Teams

8.4.2.1. Research Stays Abroad

Iordan Iordanov spent one month at University of Luxembourg in June. The visit was partially supported by by University of Luxembourg and by the NEAT Astonishing.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. Member of Organizing Committees

Sylvain Lazard organized with S. Whitesides (Victoria University) the 15th Workshop on Computational Geometry at the Bellairs Research Institute of McGill University in Feb. (1 week workshop on invitation).

Monique Teillaud co-organized the workshop *20 years of CGAL*, with Efi Fogel, Michael Hoffmann, and Emo Welzl, Zurich, Switzerland, September 10-11, and she gave a talk.

9.1.2. Scientific Events Selection

9.1.2.1. Member of Conference Program Committees

Monique Teillaud was a member of the program committee of EuroCG, *European Workshop on Computational Geometry*.

9.1.2.2. Reviewer

All members of the team are regular reviewers for the conferences of our field, namely the *Symposium on Computational Geometry* (SoCG) and the *International Symposium on Symbolic and Algebraic Computation* (ISSAC) and also SODA, CCCG, EuroCG.

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

Monique Teillaud is a managing editor of JoCG, *Journal of Computational Geometry*. She is also a member of the Editorial Board of IJCGA, *International Journal of Computational Geometry and Applications*. She resigned from the Editorial Board of CGTA, *Computational Geometry: Theory and Applications*, after unsuccessfully trying to convince the Editorial Board to leave Elsevier and move to a free (libre and gratis) open-access model.

Marc Pouget and Monique Teillaud are members of the CGAL editorial board.

Olivier Devillers resigned from the Editorial Board of Graphical Models (Elsevier) after discussion to move to a free open-access model.

9.1.3.2. Reviewer - Reviewing Activities

All members of the team are regular reviewers for the journals of our field, namely *Discrete and Computational Geometry* (DCG), *Computational Geometry. Theory and Applications* (CGTA), *Journal of Computational Geometry* (JoCG), *International Journal on Computational Geometry and Applications* (IJCGA), *Journal on Symbolic Computations* (JSC), *SIAM Journal on Computing* (SICOMP), *Mathematics in Computer Science* (MCS), etc.

9.1.4. Invited Talks

Olivier Devillers was invited to give a talk at the geometry week organized by GipsaLab in Grenoble.

Guillaume Moroz was invited to give talks at the LIGM seminar in Marne-la-Vallée university, at the SpecFun team seminary in Inria Saclay and at the MSDOS workshop in CIRM.

Monique Teillaud was invited to give a talk talk at the seminar *Computer Science meets Mathematics* of the University of Luxembourg, February 8: "CGAL, geometry made practical". She was invited to give a talk at the *Mittagsseminar* of Institute of Theoretical Computer Science of ETH Zürich on September 8: "Delaunay triangulations on orientable surfaces of low genus".

9.1.5. Seminar Organization

We invited:

Kacper Pluta (LIGM - Laboratoire d'Informatique Gaspard-Monge),

Mickaël Buchet (Tohoku University).

Andrew Yarmola (University of Luxembourg).

9.1.6. Leadership within the Scientific Community

9.1.6.1. Steering Committees

M. Teillaud has been elected Chair of the Steering Committee of the Symposium on Computational Geometry (SoCG). She is a member of the Steering Committee of the European Symposium on Algorithms (ESA).

9.1.7. Research Administration

9.1.7.1. Hiring committees

Sylvain Lazard was president of the hiring committee for a Professor position (UL/École des Mines/LORIA).

Monique Teillaud was the representative of LORIA in the hiring committee for an Associate Professor (MCF) position (École des Mines/LORIA) and composed the committee with the president. She was also a member of the Inria CR2 Nancy - Grand Est interview committee and of the hiring committee for a Professor position (FST/LORIA).

9.1.7.2. National committees

L. Dupont is a member of “Commission Pédagogique Nationale” (CPN) Information-Communication / Métiers du Multimédia et de l’Internet.

M. Teillaud is a member of the Scientific Board of the *Société Informatique de France* (SIF).

M. Teillaud is a member of the working group for the BIL, *Base d’Information des Logiciels* of Inria.

9.1.7.3. Local Committees and Responsabilities

S. Lazard: Head of the PhD and Post-doc hiring committee for Inria Nancy-Grand Est (since 2009). Member of the *Bureau de la mention informatique* of the *École Doctorale IAE+M* (since 2009). Head of the *Mission Jeunes Chercheurs* for Inria Nancy-Grand Est (since 2011). Head of the Department Algo at LORIA (since 2014). Member of the *Conseil Scientifique* of LORIA (since 2014).

G. Moroz is member of the Mathematics Olympiades committee of the Nancy-Metz academy. G. Moroz is member of the *Comité des utilisateurs des moyens informatiques*

M. Pouget is elected at the *Comité de centre*, and member of the board of the Charles Hermite federation of labs. M. Pouget is secretary of the board of *AGOS-Nancy*.

M. Teillaud is a member of the BCP, *Bureau du Comité des Projets* and of the CDT, *Commission de développement technologique* of Inria Nancy - Grand Est.

9.1.7.4. Websites

M. Teillaud is maintaining the Computational Geometry Web Pages http://www.computational-geometry.org/, hosted by Inria Nancy - Grand Est since December. This site offers general interest information for the computational geometry community, in particular the Web proceedings of the Video Review of Computational Geometry, part of the Annual/international Symposium on Computational Geometry.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master : O. Devillers, *Synthèse, image et géométrie* , 12h (academic year 2015-16) and 12h (academic year 2016-2017), IPAC-R, Université de Lorraine. https://members.loria.fr/ODevillers/master/

Master: Marc Pouget, *Introduction to computational geometry*, 10.5h, M2, École Nationale Supérieure de Géologie, France.

Licence: Sylvain Lazard, *Algorithms and Complexity*, 25h, L3, Université de Lorraine, France.

Licence: Laurent Dupont, *Algorithmique*, 78h, L1, Université de Lorraine, France.

Licence: Laurent Dupont, *Web development*, 75h, L2, Université de Lorraine, France.

Licence: Laurent Dupont, *Traitement Numérique du Signal*, 10h, L2, Université de Lorraine, France.

Licence: Laurent Dupont, *Data structures*, 40h, L1, Université de Lorraine, France.

9.2.2. Supervision

PhD : Ranjan Jha, Étude de l'espace de travail des mécanismes à boucles fermées, defended in Jul. 2016, supervised by Damien Chablat, Fabrice Rouillier and Guillaume Moroz.

PhD in progress : Sény Diatta, Complexité du calcul de la topologie d'une courbe dans l'espace et d'une surface, started in Nov. 2014, supervised by Daouda Niang Diatta, Marie-Françoise Roy and Guillaume Moroz.

PhD in progress : Charles Duménil, Probabilistic analysis of geometric structures, started in Oct. 2016, supervised by Olivier Devillers.

PhD in progress : Iordan Iordanov, Triangulations of Hyperbolic Manifolds, started in Jan. 2016, supervised by Monique Teillaud.

Postdoc: Rémy Imbach, Topology and geometry of singular surfaces with numerical algorithms, supervised by Guillaume Moroz and Marc Pouget.

9.2.3. Juries

O. Devillers was president of the PhD defense committee of Vincent Despré (Univ. Grenoble-Alpes).

G. Moroz was in the PhD defense committee of Ranjan Jha (IRCCyN).

9.2.4. Teaching Responsabilities

Licence: Laurent Dupont, creation and opening of L3 (Licence Professionnelle) « Animation des Communautés et Réseaux Socionumériques », Université de Lorraine, France.

10. Bibliography

Major publications by the team in recent years

[1] Y. BOUZIDI, S. LAZARD, M. POUGET, F. ROUILLIER.*Separating linear forms and Rational Univariate Representations of bivariate systems*, in "Journal of Symbolic Computation", 2015, p. 84-119, https://hal.inria.fr/hal-00977671.

[2] H. BRÖNNIMANN, O. DEVILLERS, V. DUJMOVIC, H. EVERETT, M. GLISSE, X. GOAOC, S. LAZARD, H.-S. NA, S. WHITESIDES.*Lines and free line segments Tangent to Arbitrary Three-dimensional Convex Polyhedra*, in "SIAM Journal on Computing", 2007, vol. 37, n° 2, p. 522-551 [*DOI :* 10.1137/S0097539705447116].

[3] J. CHENG, S. LAZARD, L. PEÑARANDA, M. POUGET, F. ROUILLIER, E. TSIGARIDAS.*On the topology of real algebraic plane curves*, in "Mathematics in Computer Science", 2010, vol. 4, n° 1, p. 113-137 [*DOI :* 10.1007/s11786-010-0044-3], https://hal.inria.fr/inria-00517175.

[4] O. DEVILLERS, M. GLISSE, X. GOAOC.*Complexity Analysis of Random Geometric Structures Made Simpler*, in "29th Annual Symposium on Computational Geometry", Rio, Brazil, June 2013, p. 167-175 [*DOI :* 10.1145/2462356.2462362], https://hal.inria.fr/hal-00833774.

[5] L. DUPONT, D. LAZARD, S. LAZARD, S. PETITJEAN.*Near-Optimal Parameterization of the Intersection of Quadrics: I. The Generic Algorithm; II. A Classification of Pencils; III. Parameterizing Singular Intersections*, in "Journal of Symbolic Computation", 2008, vol. 43, p. 168–191, 192–215, 216–232, http://hal.inria.fr/inria-00186090/en/.

[6] H. EVERETT, D. LAZARD, S. LAZARD, M. SAFEY EL DIN.*The Voronoi diagram of three lines*, in "Journal of Discrete and Computational Geometry", 2009, vol. 42, n^{o} 1, p. 94-130 [*DOI :* 10.1007/S00454-009-9173-3], http://www.springerlink.com/content/f5601q6324664k2p/?p=6d7bb74bf9df40b0b7756b3a5153809f&pi=5.

[7] M. GLISSE, S. LAZARD.*An Upper Bound on the Average Size of Silhouettes*, in "Discrete & Computational Geometry", 2008, vol. 40, n^{o} 2, p. 241-257 [*DOI :* 10.1007/S00454-008-9089-3].

[8] X. GOAOC, H.-S. KIM, S. LAZARD.*Bounded-Curvature Shortest Paths through a Sequence of Points using Convex Optimization*, in "SIAM Journal on Computing", 2013, vol. 42, n^{o} 2, p. 662-684 [*DOI :* 10.1137/100816079], https://hal.inria.fr/hal-00927100.

[9] M. HEMMER, L. DUPONT, S. PETITJEAN, E. SCHÖMER.*A Complete, Exact and Efficient Implementation for Computing the Edge-Adjacency Graph of an Arrangement of Quadrics*, in "Journal of Symbolic Computation", 2011, vol. 46, n^{o} 4, p. 467-494 [*DOI :* 10.1016/J.JSC.2010.11.002], https://hal.inria.fr/inria-00537592.

Publications of the year

Articles in International Peer-Reviewed Journal

[10] D. ATTALI, O. DEVILLERS, M. GLISSE, S. LAZARD.*Recognizing Shrinkable Complexes Is NP-Complete*, in "Journal of Computational Geometry", 2016, vol. 7, n^{o} 1, p. 430–443 [*DOI :* 10.20382/JOCG.V7I1A18], https://hal.inria.fr/hal-01384396.

[11] Y. BOUZIDI, S. LAZARD, G. MOROZ, M. POUGET, F. ROUILLIER, M. SAGRALOFF.*Solving bivariate systems using Rational Univariate Representations*, in "Journal of Complexity", 2016, vol. 37, p. 34–75 [*DOI :* 10.1016/J.JCO.2016.07.002], https://hal.inria.fr/hal-01342211.

[12] N. BROUTIN, O. DEVILLERS, R. HEMSLEY.*Efficiently navigating a random Delaunay triangulation*, in "Random Structures and Algorithms", 2016, vol. 49, n^{o} 1, p. 95–136 [*DOI :* 10.1002/RSA.20630], https://hal.inria.fr/hal-00940743.

[13] M. CAROLI, M. TEILLAUD.*Delaunay triangulations of closed Euclidean d-orbifolds*, in "Discrete and Computational Geometry", 2016, vol. 55, n^{o} 4, p. 827–853 [*DOI :* 10.1007/S00454-016-9782-6], https://hal.inria.fr/hal-01294409.

[14] O. DEVILLERS, M. GLISSE, X. GOAOC, R. THOMASSE.*Smoothed complexity of convex hulls by witnesses and collectors*, in "Journal of Computational Geometry", 2016, vol. 7, n^{o} 2, p. 101-144 [*DOI :* 10.20382/JOCG.V7I2A6], https://hal.inria.fr/hal-01285120.

[15] O. DEVILLERS, R. HEMSLEY.*The worst visibility walk in a random Delaunay triangulation is $O(\sqrt{n})$*, in "Journal of Computational Geometry", 2016, vol. 7, n^{o} 1, p. 332-359 [*DOI :* 10.20382/JOCG.V7I1A16], https://hal.inria.fr/hal-01348831.

[16] M. GLISSE, S. LAZARD, J. MICHEL, M. POUGET.*Silhouette of a random polytope*, in "Journal of Computational Geometry", 2016, vol. 7, n^{o} 1, 14, https://hal.inria.fr/hal-01289699.

[17] R. IMBACH, G. MOROZ, M. POUGET.*A certified numerical algorithm for the topology of resultant and discriminant curves*, in "Journal of Symbolic Computation", 2016, vol. 80, Part 2, p. 285–306 [*DOI :* 10.1016/J.JSC.2016.03.011], https://hal.inria.fr/hal-01402194.

[18] P. KAMOUSI, S. LAZARD, A. MAHESHWARI, S. WUHRER.*Analysis of Farthest Point Sampling for Approximating Geodesics in a Graph*, in "Computational Geometry", 2016, vol. 57, p. 1-7 [*DOI :* 10.1016/J.COMGEO.2016.05.005], https://hal.inria.fr/hal-01297624.

[19] G. MOROZ, B. ARONOV.*Computing the Distance between Piecewise-Linear Bivariate Functions*, in "ACM Transactions on Algorithms", February 2016, vol. 12, n^{o} 1, p. 3:1-3:13, https://hal.archives-ouvertes.fr/hal-01112394.

International Conferences with Proceedings

[20] M. BOGDANOV, M. TEILLAUD, G. VEGTER.*Delaunay triangulations on orientable surfaces of low genus*, in "International Symposium on Computational Geometry", Boston, United States, June 2016, p. 20:1–20:15 [*DOI :* 10.4230/LIPICS.SOCG.2016.20], https://hal.inria.fr/hal-01276386.

[21] D. BREMNER, O. DEVILLERS, M. GLISSE, S. LAZARD, G. LIOTTA, T. MCHEDLIDZE, S. WHITESIDES, S. WISMATH.*Monotone Simultaneous Paths Embeddings in $\mathbb{R}^d$*, in "24th International Symposium on Graph Drawing & Network Visualization", Athens, Greece, Proceedings of 24th International Symposium on Graph Drawing & Network Visualization, Springer, September 2016, vol. 9801, https://hal.inria.fr/hal-01366148.

[22] O. DEVILLERS, M. KARAVELAS, M. TEILLAUD.*Qualitative Symbolic Perturbation*, in "SoCG 2016 - International Symposium on Computational Geometry", Boston, United States, June 2016, p. 33:1-33:15 [*DOI :* 10.4230/LIPICS.SOCG.2016.33], https://hal.inria.fr/hal-01276444.

[23] R. JHA, D. CHABLAT, F. ROUILLIER, G. MOROZ.*Influence of the trajectory planning on the accuracy of theorthoglide 5-axis*, in "ASME International Design Engineering Technical Conference and the Computer and Information in Engineering Conference (IDETC/CIE)", Charlotte, NC, United States, August 2016, https://hal.archives-ouvertes.fr/hal-01309190.

[24] G. MOROZ, É. SCHOST.*A Fast Algorithm for Computing the Truncated Resultant*, in "ISSAC '16", Waterloo, Canada, M. ROSENKRANZ (editor), Proceedings of the ACM on International Symposium on Symbolic and Algebraic Computation, ACM, July 2016, p. 341-348 [*DOI :* 10.1145/2930889.2930931], https://hal.archives-ouvertes.fr/hal-01366386.

[25] K. PLUTA, G. MOROZ, Y. KENMOCHI, P. ROMON.*Quadric arrangement in classifying rigid motions of a 3D digital image*, in "The 18th International Workshop on Computer Algebra in Scientific Computing", Bucharest, Romania, Lecture Notes in Computer Science, Springer, June 2016, vol. volume 9890, https://hal.archives-ouvertes.fr/hal-01334257.

Research Reports

[26] N. CHENAVIER, O. DEVILLERS.*Stretch Factor of Long Paths in a planar Poisson-Delaunay Triangulation*, Inria, July 2016, n^{o} RR-8935, 34, https://hal.inria.fr/hal-01346203.

[27] O. DEVILLERS, L. NOIZET.*Walking in a Planar Poisson-Delaunay Triangulation: Shortcuts in the Voronoi Path*, Inria Nancy, August 2016, n^o RR-8946, https://hal.inria.fr/hal-01353585.

[28] R. IMBACH.*A Subdivision Solver for Systems of Large Dense Polynomials*, Inria Nancy, March 2016, n^o RT-0476, 13, https://hal.inria.fr/hal-01293526.

[29] R. IMBACH, P. MATHIS, P. SCHRECK.*A Robust and Efficient Method for Solving Point Distance Problems by Homotopy*, Inria, July 2016, n^o RR-8705, https://hal.inria.fr/hal-01135230.

[30] I. IORDANOV, M. TEILLAUD.*Implementing Delaunay triangulations of the Bolza surface*, Inria Nancy, 2016, n^o RR-8994, https://hal.inria.fr/hal-01411415.

[31] P. MACHADO MANHÃES DE CASTRO, O. DEVILLERS.*Expected Length of the Voronoi Path in a High Dimensional Poisson-Delaunay Triangulation*, Inria, August 2016, n^o RR-8947, https://hal.inria.fr/hal-01353735.

References in notes

[32] *QI: a C++ package for parameterizing intersections of quadrics*, 2005, LORIA, Inria Lorraine, VEGAS project, http://www.loria.fr/equipes/vegas/qi.

Project-Team VERIDIS

Modeling and Verification of Distributed Algorithms and Systems

IN COLLABORATION WITH: Laboratoire lorrain de recherche en informatique et ses applications (LORIA)

IN PARTNERSHIP WITH:
CNRS

Max Planck Institut für Informatik de Saarbrücken

Université de Lorraine

RESEARCH CENTER
Nancy - Grand Est

THEME
Proofs and Verification

Table of contents

Project-Team VERIDIS

Creation of the Team: 2010 January 01, updated into Project-Team: 2012 July 01

Keywords:

Computer Science and Digital Science:

2.1.7. - Distributed programming
2.1.11. - Proof languages
2.4. - Verification, reliability, certification
2.4.1. - Analysis
2.4.2. - Model-checking
2.4.3. - Proofs
7.4. - Logic in Computer Science
7.6. - Computer Algebra

Other Research Topics and Application Domains:

6.1. - Software industry
6.3.2. - Network protocols
6.6. - Embedded systems

1. Members

Research Scientists

Jasmin Christian Blanchette [Inria, Starting Research Position]
Stephan Merz [Team leader, Inria, Senior Researcher, HDR]
Thomas Sturm [CNRS, Senior Researcher]
Uwe Waldmann [Max-Planck Institut für Informatik, Senior Researcher]
Christoph Weidenbach [Team leader, Max-Planck Institut für Informatik, Senior Researcher, HDR]

Faculty Members

Marie Duflot-Kremer [Univ. Lorraine, Associate Professor]
Pascal Fontaine [Univ. Lorraine, Associate Professor]
Dominique Méry [Univ. Lorraine, Professor, HDR]
Martin Strecker [Univ. Toulouse III, Associate Professor, Inria secondment since Sep 2016]

Technical Staff

Gabriel Corona [Univ. Lorraine, until Aug 2016]
Simon Cruanes [Inria]
Matthieu Nicolas [Inria]
Martin Riener [Inria, MSR-Inria Joint Centre]

PhD Students

Gabor Alági [Univ. des Saarlandes, since Nov 2012]
Noran Azmy [Univ. des Saarlandes, until Aug 2016]
Haniel Barbosa [Univ. Lorraine, since Dec 2013]
Martin Bromberger [Univ. des Saarlandes, since Jul 2014]
Margaux Duroeulx [Univ. Lorraine, since Oct 2016]
Mathias Fleury [Univ. des Saarlandes, since Oct 2015]
Souad Kherroubi [Univ. Lorraine, since Jan 2015]
Marek Košta [Univ. des Saarlandes, until Oct 2016]

Nicolas Schnepf [Inria, since Oct 2016]
Marco Voigt [Univ. des Saarlandes, since Nov 2013]
Daniel Wand [Univ. des Saarlandes, since Feb 2011]

Administrative Assistants

Sophie Drouot [Inria]
Martine Kuhlmann [CNRS]
Jennifer Müller [Max-Planck Institut für Informatik]

Others

Ilina Stoilkovska [TU Wien, visitor, Sep–Oct 2016]
Tung Vu Xuan [JAIST, visitor, since May 2016]

2. Overall Objectives

2.1. Overall Objectives

The VeriDis project team includes members of the MOSEL group at LORIA, the computer science laboratory in Nancy, and members of the research group *Automation of Logic* at Max-Planck-Institut für Informatik in Saarbrücken. It is headed by Stephan Merz and Christoph Weidenbach. VeriDis was created in 2010 as a local research group of Inria Nancy – Grand Est and has been an Inria project team since July 2012.

The objectives of VeriDis are to contribute to advances in verification techniques, including automated and interactive theorem proving, and to make them available for the formal development and analysis of concurrent and distributed algorithms and systems, within the framework of mathematically precise and practically applicable development methods. We intend to assist designers of algorithms and systems in carrying out formally proved developments, where proofs of relevant properties, as well as bugs, can be found with a high degree of automation.

Verification techniques based on theorem proving are already having substantial impact. In particular, they have been successfully applied to the verification and analysis of sequential programs, often in combination with static analysis and software model checking. Ideally, systems and their properties would be specified in high-level, expressive languages, errors in specifications would be discovered automatically, and finally, full verification could also be performed completely automatically. Due to the inherent complexity of the problem, this cannot be achieved in general. We have, however, observed significant advances in theorem proving in recent years. We are particularly interested in the integration of different deduction techniques and tools, such as automated theorem proving for relevant theories, such as different fragments of arithmetic. These advances suggest that a substantially higher degree of automation can be achieved in system verification than what is available in today's verification tools.

VeriDis aims at exploiting and further developing automation in system verification, and at applying its techniques within the context of concurrent and distributed algorithms, which are by now ubiquitous and whose verification is a big challenge. Concurrency problems are central for the development and verification of programs for multi- and many-core architectures, and distributed computation underlies the paradigms of grid and cloud computing. The potential of distributed systems for increased resilience to component failures makes them attractive in many contexts, but also makes formal verification important and challenging. We aim at moving current research in this area to a new level of productivity and quality. To give a concrete example: today the designer of a new distributed protocol may validate it using testing or model checking. Model checking will help finding bugs, but can only guarantee properties of a high-level model of the protocol, usually restricted to finite instances. Testing distributed systems and protocols is notoriously difficult because corner cases are hard to establish and reproduce. Also, many testing techniques require an executable, whose production is expensive and time-consuming, and since an implementation is needed, errors are found only when they are expensive to fix. The techniques that we develop aim at automatically proving significant properties of the protocol already during the design phase. Our methods mainly target designs and algorithms at high levels of abstraction; we aim at components of operating systems, distributed services, and down to the (mobile) network systems industry.

3. Research Program

3.1. Automated and Interactive Theorem Proving

The VeriDis team gathers experts in techniques and tools for automatic deduction and interactive theorem proving, and specialists in methods and formalisms designed for the development of trustworthy concurrent and distributed systems and algorithms. Our common objective is twofold: first, we wish to advance the state of the art in automated and interactive theorem proving, and their combinations. Second, we work on making the resulting technology available for the computer-aided verification of distributed systems and protocols. In particular, our techniques and tools are intended to support sound methods for the development of trustworthy distributed systems that scale to algorithms relevant for practical applications.

VeriDis members from Saarbrücken are developing SPASS [10], one of the leading automated theorem provers for first-order logic based on the superposition calculus [39]. The group also studies general frameworks for the combination of theories such as the locality principle [52] and automated reasoning mechanisms these induce.

In a complementary approach to automated deduction, VeriDis members from Nancy work on techniques for integrating reasoners for specific theories. They develop veriT [1], an SMT (Satisfiability Modulo Theories [41]) solver that combines decision procedures for different fragments of first-order logic and that integrates an automatic theorem prover for full first-order logic. The veriT solver is designed to produce detailed proofs; this makes it particularly suitable as a component of a robust cooperation of deduction tools.

Finally, VeriDis members design effective quantifier elimination methods and decision procedures for algebraic theories, supported by their efficient implementation in the Redlog system [4].

An important objective of this line of work is the integration of theories in automated deduction. Typical theories of interest, including fragments of arithmetic, are not expressible in first-order logic. We therefore explore efficient, modular techniques for integrating semantic and syntactic reasoning methods, develop novel combination results and techniques for quantifier instantiation. These problems are addressed from both sides, e.g. by embedding a decision procedure into the superposition framework or by allowing an SMT solver to accept axiomatizations for plug-in theories. We also develop specific decision procedures for theories such as non-linear real arithmetic that are important when reasoning about certain classes of (e.g., real-time) systems but that also have interesting applications beyond verification.

We rely on interactive theorem provers for reasoning about specifications at a high level of abstraction when fully automatic verification is not (yet) feasible. An interactive proof platform should help verification engineers lay out the proof structure at a sufficiently high level of abstraction; powerful automatic plug-ins should then discharge the resulting proof steps. Members of VeriDis have ample experience in the specification and subsequent machine-assisted, interactive verification of algorithms. In particular, we participate in a project at the joint Microsoft Research-Inria Centre in Saclay on the development of methods and tools for the formal proof of TLA$^+$ [45] specifications. Our prover relies on a declarative proof language, and calls upon several automatic backends [3]. Trust in the correctness of the overall proof can be ensured when the backends provide justifications that can be checked by the trusted kernel of a proof assistant. During the development of a proof, most obligations that are passed to the prover actually fail – for example, because necessary information is not present in the context or because the invariant is too weak, and we are interested in explaining failed proof attempts to the user, in particular through the construction of counter-models.

3.2. Formal Methods for Developing and Analyzing Algorithms and Systems

Theorem provers are not used in isolation, but they support the application of sound methodologies for modeling and verifying systems. In this respect, members of VeriDis have gained expertise and recognition in making contributions to formal methods for concurrent and distributed algorithms and systems [2], [9], and in applying them to concrete use cases. In particular, the concept of *refinement* [38], [40], [48] in state-based modeling formalisms is central to our approach because it allows us to present a rational (re)construction of system development. An important goal in designing such methods is to establish precise proof obligations many of which can be discharged by automatic tools. This requires taking into account specific characteristics of certain classes of systems and tailoring the model to concrete computational models. Our research in this area is supported by carrying out case studies for academic and industrial developments. This activity benefits from and influences the development of our proof tools.

In this line of work, we investigate specific development and verification patterns for particular classes of algorithms, in order to reduce the work associated with their verification. We are also interested in applications of formal methods and their associated tools to the development of systems that underlie specific certification requirements in the sense of, e.g., Common Criteria. Finally, we are interested in the adaptation of model checking techniques for verifying actual distributed programs, rather than high-level models.

Today, the formal verification of a new algorithm is typically the subject of a PhD thesis, if it is addressed at all. This situation is not sustainable given the move towards more and more parallelism in mainstream systems: algorithm developers and system designers must be able to productively use verification tools for validating their algorithms and implementations. On a high level, the goal of VeriDis is to make formal verification standard practice for the development of distributed algorithms and systems, just as symbolic model checking has become commonplace in the development of embedded systems and as security analysis for cryptographic protocols is becoming standard practice today. Although the fundamental problems in distributed programming are well-known, they pose new challenges in the context of modern system paradigms, including ad-hoc and overlay networks or peer-to-peer systems, and they must be integrated for concrete applications.

4. Application Domains

4.1. Application Domains

Distributed algorithms and protocols are found at all levels of computing infrastructure, from many-core processors and systems-on-chip to wide-area networks. We are particularly interested in the verification of algorithms that are developed for supporting novel computing paradigms, including ad-hoc networks that underly mobile and low-power computing or overlay networks and peer-to-peer networking that provide services for telecommunication or cloud computing services. Computing infrastructure must be highly available and is ideally invisible to the end user, therefore correctness is crucial. One should note that standard problems of distributed computing such as consensus, group membership or leader election have to be reformulated for the dynamic context of these modern systems. We are not ourselves experts in the design of distributed algorithms, but we work together with domain experts on designing formal models of these protocols, and on verifying their properties. These cooperations help us focus on concrete algorithms and ensure that our work is relevant to the distributed algorithm community.

Formal verification techniques can contribute to certifying the correctness of systems. In particular, they help assert under which assumptions an algorithm or system functions as required. For example, the highest levels of the Common Criteria for Information Technology Security Evaluation encourage the use of formal methods. While initially the requirements of certified development have mostly been restricted to safety-critical systems, the cost of unavailable services due to malfunctioning system components and software provides wider incentives for verification. For example, we are working on modeling and verifying medical devices that require closed-loop models of both the system and its environment.

5. Highlights of the Year

5.1. Highlights of the Year

Jasmin Blanchette was awarded an ERC Starting Grant for his Matryoshka project aiming at fast interactive verification through strong automation for higher-order constructs.

As part of a European network, Pascal Fontaine and Thomas Sturm participate in a new H2020 Coordination and Support Action. [0] In accordance with the distributed character of Veridis, we are operating nodes at LORIA as well as MPI. Further nodes are located in Austria (University of Linz), Germany (RWTH Aachen; University of Kassel), Italy (Fondazione Bruno Kessler; University of Genova), and the UK (Universties of Bath, Coventry, and Oxford; Maplesoft Europe Ltd.). The CSA aims at improving the integration of communities, methods, and software from SMT solving and symbolic computation [20].

Jasmin Blanchette and Stephan Merz were PC chairs and organizers of the 7th International Conference on Interactive Theorem Proving in Nancy (August 22–27), the main conference of developers and users of proof assistants.

5.1.1. Awards

Mathias Fleury, together with his two supervisors, received the Best Paper Award at IJCAR 2016 for their work on a formalized SAT solver.

Together with Andrew J. Reynolds at the University of Iowa, Jasmin Blanchette was invited to submit a short version of his CADE 2015 paper on a decision procedure for (co)datatypes to the Sister Conference Best Paper Track of IJCAI 2016.
BEST PAPERS AWARDS :
[25] **8th International Joint Conference on Automated Reasoning (IJCAR 2016)**. J. C. BLANCHETTE, M. FLEURY, C. WEIDENBACH.
[19] **IJCAI 2016**. A. REYNOLDS, J. C. BLANCHETTE.

6. New Software and Platforms

6.1. The Nunchaku Higher-Order Model Finder

FUNCTIONAL DESCRIPTION

Nunchaku is a model finder for higher-order logic, with dedicated support for various definitional principles. It is designed to work as a backend for various proof assistants and to use state-of-the-art model finders and other solvers as backends.

In 2016, the first three versions of the tools were released (0.1 through 0.3). The Isabelle2016-1 release includes Nunchaku as well as the frontend that bridges the gap between the proof assistant and the model finder. Work has commenced on a Coq frontend [28] and a TLA$^+$ frontend. Currently, the backends CVC4, Kodkod, and Paradox are supported.

- Participants: Jasmin Blanchette and Simon Cruanes
- Contact: Jasmin Blanchette
- URL: https://github.com/nunchaku-inria

6.2. The Redlog Computer Logic System

FUNCTIONAL DESCRIPTION

Redlog is an integral part of the interactive computer algebra system Reduce. It supplements Reduce's comprehensive collection of powerful methods from symbolic computation by supplying more than 100 functions on first-order formulas.

Redlog generally works with interpreted first-order logic in contrast to free first-order logic. Each first-order formula in Redlog must exclusively contain atoms from one particular Redlog-supported theory, which corresponds to a choice of admissible functions and relations with fixed semantics. Redlog-supported theories include Nonlinear Real Arithmetic (Real Closed Fields), Presburger Arithmetic, Parametric QSAT, and many more.

[0] H2020-FETOPEN-2015-CSA-712689, http://www.sc-square.org/

In 2016 there was significant progress with the generation of models for real satisfiability problems [15]. When obtained via quantifier elimination by virtual substitutions, such models contain in general non-standard numbers like positive infinitesimal and infinite values. In an efficient post-processing step Redlog now generates standard models.

- Participants: Thomas Sturm and Marek Kosta
- Contact: Thomas Sturm
- URL: http://www.redlog.eu/

6.3. The SPASS automated theorem prover

FUNCTIONAL DESCRIPTION

The classic SPASS is an automated theorem prover based on superposition that handles first-order logic with equality and several extensions for particular classes of theories. With version SPASS 3.9 we have stopped the development of the classic prover and have started the bottom-up development of SPASS 4.0 that will actually be a workbench of automated reasoning tools.

In 2016 we have made available for the first time our LIA solver SPASS-IQ. Furthermore, we have developed a state-of-the-art SAT solver SPASS-SATT that will be available in 2017.

- Contact: Christoph Weidenbach
- URL: http://www.spass-prover.org/

6.4. TLAPS, the TLA+ Proof System

FUNCTIONAL DESCRIPTION

TLAPS, the TLA$^+$ proof system developed at the Joint MSR-Inria Centre, is a platform for developing and mechanically verifying proofs about TLA$^+$ specifications. The TLA$^+$ proof language is hierarchical and explicit, allowing a user to decompose the overall proof into independent proof steps. TLAPS consists of a *proof manager* that interprets the proof language and generates a collection of proof obligations that are sent to *backend verifiers*. The current backends include the tableau-based prover Zenon for first-order logic, Isabelle/TLA$^+$, an encoding of TLA$^+$ as an object logic in the logical framework Isabelle, an SMT backend designed for use with any SMT-lib compatible solver, and an interface to a decision procedure for propositional temporal logic.

The current version 1.4.3 of TLAPS was released in June 2015, it is distributed under a BSD-like license. The prover fully handles the non-temporal part of TLA$^+$. Basic temporal logic reasoning is supported through an interface with a decision procedure for propositional temporal logic that performs on-the-fly abstraction of first-order subformulas. Symmetrically, subformulas whose main operator is a connective of temporal logic are abstracted before being sent to backends for first-order logic.

A complete rewrite of the proof manager is ongoing. Its objectives are a cleaner interaction with the standard TLA$^+$ front-ends, in particular SANY, the standard parser and semantic analyzer. This is necessary for extending the scope of the fragment of TLA$^+$ that is handled by TLAPS, such as full temporal logic and module instantiation.

TLAPS has been used in several case studies, including the proof of determinacy of PharOS [21] and the verification of the Pastry routing protocol [22]. These case studies feed back into the development of the proof system and of its standard library.

- Contact: Stephan Merz
- URL: https://tla.msr-inria.inria.fr/tlaps/content/Home.html

6.5. The veriT Solver

SCIENTIFIC DESCRIPTION

veriT comprises a SAT solver, a congruence closure based decision procedure for uninterpreted symbols, a simplex-based decision procedure for linear arithmetic, and instantiation-based quantifier handling.

FUNCTIONAL DESCRIPTION

VeriT is an open, trustable and efficient SMT (Satisfiability Modulo Theories) solver, featuring efficient decision procedure for uninterpreted symbols and linear arithmetic, and quantifier reasoning.

Efforts in 2016 have been focused on non-linear arithmetic reasoning and quantifier handling. The reasoning capabilities of veriT have been significantly improved along those two axes, but non-linear arithmetic reasoning is not yet stable.

The veriT solver participated in the SMT competition SMT-COMP 2016 with good results.

We target applications where validation of formulas is crucial, such as the validation of TLA^+ and B specifications, and work together with the developers of the respective verification platforms to make veriT even more useful in practice. The solver is available as a plugin for the Rodin platform, it is integrated within the Atelier B.

- Participants: Pascal Fontaine, David Déharbe and Haniel Barbosa
- Partners: Université de Lorraine - Federal University of Rio Grande do Norte
- Contact: Pascal Fontaine
- URL: http://www.veriT-solver.org

7. New Results

7.1. Automated and Interactive Theorem Proving

Participants: Gabor Alági, Haniel Barbosa, Jasmin Christian Blanchette, Martin Bromberger, Simon Cruanes, Mathias Fleury, Pascal Fontaine, Marek Košta, Stephan Merz, Martin Riener, Martin Strecker, Thomas Sturm, Marco Voigt, Uwe Waldmann, Daniel Wand, Christoph Weidenbach.

7.1.1. IsaFoL: Isabelle Formalization of Logic

Joint work with Heiko Becker (MPI-SWS Saarbrücken), Peter Lammich (TU München), Andrei Popescu (Middlesex University London), Anders Schlichtkrull (DTU Copenhagen), Dmitriy Traytel (ETH Zürich), and Jørgen Villadsen (DTU Copenhagen).

Researchers in automated reasoning spend a significant portion of their work time specifying logical calculi and proving metatheorems about them. These proofs are typically carried out with pen and paper, which is error-prone and can be tedious. As proof assistants are becoming easier to use, it makes sense to employ them.

In this spirit, we started an effort, called IsaFoL (Isabelle Formalization of Logic), that aims at developing libraries and methodology for formalizing modern research in the field, using the Isabelle/HOL proof assistant.[0] Our initial emphasis is on established results about propositional and first-order logic. In particular, we are formalizing large parts of Weidenbach's forthcoming textbook, tentatively called *Automated Reasoning—The Art of Generic Problem Solving*.

The objective of formalization work is not to eliminate paper proofs, but to complement them with rich formal companions. Formalizations help catch mistakes, whether superficial or deep, in specifications and theorems; they make it easy to experiment with changes or variants of concepts; and they help clarify concepts left vague on paper.

[0] https://bitbucket.org/jasmin_blanchette/isafol/wiki/Home

The repository contains six completed entries and three entries that are still in development. Notably:

- Mathias Fleury formalized a SAT solver framework with learn, forget, restart, and incrementality and published the result at a leading conference, together with Jasmin Blanchette and Christoph Weidenbach [25].
- Anders Schlichtkrull, remotely co-supervised by Jasmin Blanchette, formalized unordered first-order resolution in Isabelle and presented the result at ITP 2016 [37].
- Together with an intern, Jasmin Blanchette, Uwe Waldmann, and Daniel Wand formalized a generalization for the recursive path order and the transfinite Knuth-Bendix order to higher-order terms without λ-abstractions. The result is published in the Isabelle *Archive of Formal Proofs*.

7.1.2. Combination of Satisfiability Procedures

Joint work with Christophe Ringeissen from the PESTO project-team at Inria Nancy – Grand Est, and Paula Chocron at IIIA-CSIC, Bellaterra, Catalonia, Spain.

A satisfiability problem is often expressed in a combination of theories, and a natural approach consists in solving the problem by combining the satisfiability procedures available for the component theories. This is the purpose of the combination method introduced by Nelson and Oppen. However, in its initial presentation, the Nelson-Oppen combination method requires the theories to be signature-disjoint and stably infinite (to ensure the existence of an infinite model). The design of a generic combination method for non-disjoint unions of theories is clearly a hard task, but it is worth exploring simple non-disjoint combinations that appear frequently in verification. An example is the case of shared sets, where sets are represented by unary predicates. Another example is the case of bridging functions between data structures and a target theory (e.g., a fragment of arithmetic).

In 2015, we defined [42] a sound and complete combination procedure à la Nelson-Oppen for the theory of absolutely free data structures (including lists and trees) connected to another theory via bridging functions. This combination procedure has also been refined for standard interpretations. The resulting theory has a nice politeness property, enabling combinations with arbitrary decidable theories of elements. We also investigated [43] other theories amenable to similar combinations: this class includes the theory of equality, the theory of absolutely free data structures, and all the theories in between.

More recently, we have been improving the framework and unified both results. A new paper is in preparation.

7.1.3. Quantifier handling in SMT

Joint work with Andrew J. Reynolds, Univ. of Iowa, USA.

SMT solvers generally rely on various instantiation techniques to handle quantifiers. We are building a unifying framework for handling quantified formulas with equality and uninterpreted functions, such that the major instantiation techniques in SMT solving can be cast in that framework. It is based on the problem of E-ground (dis)unification, a variation of the classic Rigid E-unification problem. We introduced a sound and complete calculus to solve this problem in practice: Congruence Closure with Free Variables (CCFV). Experimental evaluations of implementations of CCFV in the state-of-the-art solver CVC4 and in the solver veriT exhibit improvements in the former and makes the latter competitive with state-of-the-art solvers in several benchmark libraries stemming from verification efforts. A publication is in preparation.

7.1.4. Non-linear arithmetic in SMT

In the context of the SMArT ANR-DFG (Satisfiability Modulo Arithmetic Theories) and KANASA projects (cf. sections 9.1 and 9.3), we study the theory, design techniques, and implement software to push forward the non-linear arithmetic (NLA) reasoning capabilities in SMT. This year, we designed a framework to combine interval constraint propagation with other decision procedures for NLA, with promising results. We are also currently studying integration of these procedures into combinations of theories. The ideas are validated within the veriT solver, together with code from the raSAT solver (from JAIST). An article is in preparation.

7.1.5. Encoding Set-Theoretic Formulas in First-Order Logic

Proof obligations that arise during the verification of high-level specifications of algorithms in languages such as (Event-)B and TLA$^+$ mix theories corresponding to sets, functions, arithmetic, tuples, and records. Finding encodings of such formulas in the input languages of automatic first-order provers (superposition-based provers or SMT solvers, which are based on multi-sorted first-order logic) is paramount for obtaining satisfactory levels of automation. We describe a method, based on a combination of injection of unsorted expressions into sorted languages, simplification by rewriting, and abstraction, that is the kernel of the SMT backend of the TLA$^+$ proof system (section 6.4). A paper describing our technique was presented at ABZ 2016 [31] and an extension of that article was invited for a special issue of Science of Computer Programming.

During the internship of Matthieu Lequesne, we experimented with an adaptation of the technique for constructing models of formulas in set theory, which could be useful for understanding why proof attempts fail. A prototype generating input for the Nunchaku model finder (section 6.1) allowed us to validate the idea for a core sublanguage of TLA$^+$.

7.1.6. Modal and Description Logics for Graph Transformations

Graph transformations are a research topic that is interesting in its own right, but with many possible applications ranging from the modification of pointer structures in imperative programs, through model transformations in model-driven engineering, to schema-preserving transformations of graph databases. Our particular focus is on verifying these transformations.

Modal logics and variants (such as description logics that are the basis for the web ontology language OWL) have turned out to be suitable specification formalisms because graph structures can typically be perceived as models of modal logics, but these logics suffer from some weaknesses when reasoning about transformations. The first aim of our work was therefore to identify and define sufficiently expressive modal logics, while retaining their pleasant properties, in particular decidability [30].

Our next aim is to implement practically useful proof methods. We have first concentrated on the more natural tableau proofs, with a verification of meta-theoretic properties of the calculi (such as termination) in the Isabelle proof assistant. We now turn to an investigation of encodings as satisfiability problems that can be handled with SAT and SMT solvers, with the hope to achieve a better performance.

7.1.7. Standard Models with Virtual Substitution

Joint work with A. Dolzmann from Leibniz-Zentrum für Informatik in Saarbrücken, Germany.

Extended quantifier elimination for the reals using virtual substitution methods have been successfully applied to various problems in science and engineering. Recently they have attracted attention also as theory solvers within SMT. Such solvers typically ask also for models in the satisfiable case. Models obtained with virtual substitution are in general obtained in certain non-archimedian extension fields of the reals with a corresponding expanded signature. Consequently, the obtained values for the variables include non-standard symbols such as positive infinitesimals and infinite values.

We introduce a complete post-processing procedure to convert our models, for fixed values of parameters, into real models [15]. We furthermore demonstrate the successful application of an implementation of our method within Redlog to a number of extended quantifier elimination problems from the scientific literature including computational geometry, motion planning, bifurcation analysis for models of genetic circuits and for mass action, and sizing of electrical networks. This solves a long-standing problem with the virtual substitution method, which had been explicitly criticized in the scientific literature.

7.1.8. Decidability of Fragments of Free First-Order Logic

We introduce a new decidable fragment of first-order logic with equality, the *Separated Fragment* (SF). It strictly generalizes two already well-known decidable fragments of first-order logic: the Bernays-Schönfinkel-Ramsey (BSR) Fragment and the Monadic Fragment. The defining principle is that universally and existentially quantified variables may not occur together in atoms. Thus, our classification neither rests on restrictions of quantifier prefixes (as in the BSR case) nor on restrictions on the arity of predicate symbols (as in the monadic case).

We show that SF exhibits the finite model property and derive a non-elementary upper bound on the computing time required for deciding satisfiability of SF sentences. For the subfragment of prenex sentences with the quantifier prefix $\exists^*\forall^*\exists^*$ the satisfiability problem is shown to be NEXPTIME-complete. Furthermore, we discuss how automated reasoning procedures can take advantage of our results [34].

Continuing the work presented in the initial publication, we further investigated the computational complexity of SF satisfiability. It nicely scales across the nondeterministic standard complexity classes, depending on joint occurrences of existentially quantified variables from $\exists^*$-blocks that are separated by nonempty $\forall^+$-blocks.

In another line of work, we relaxed the definition of SF, leading to an even larger fragment for which satisfiability is still decidable. In this fragment, variables of $\exists^*$-blocks and $\forall^+$-blocks may occur together in some atom if the respective quantifiers obey a certain order.

7.1.9. Ordered resolution with dismatching constraints

The identification and algorithmic exploration of decidable logic fragments is key to the automation of logics and to obtaining push-button verification technologies. We extend a well-known decidable fragment, linear monadic shallow Horn theories, with straight dismatching constraints, preserving decidability. Furthermore, we show that the restriction to Horn clauses is not needed. The fragment has various applications in security, automata theory and theorem proving [35].

7.1.10. Undecidable combinations of first-order logic with background theories

We show that the universal fragment of Presburger arithmetic augmented with a single uninterpreted predicate (or function) symbol is already undecidable. The result has immediate consequences for verification techniques that combine uninterpreted functions or predicate symbols with (fragments of) Presburger arithmetic. For example, data structures such as arrays can be viewed as a collection of uninterpreted functions that obey certain axioms.

Our result is a sharpening of previously known results. In particular, undecidability holds for a fragment with purely universal quantification: no quantifier alternation is necessary. While in this case the set of unsatisfiable sentences is still recursively enumerable, and in fact hierarchic superposition constitutes a semi-decision procedure, allowing for one quantifier alternation ($\exists\forall$ or $\forall\exists$) leads to a fragment in which neither the satisfiable sentences nor the unsatisfiable ones form a recursively-enumerable set. Hence, there cannot be any refutationally complete calculus for such a combined theory.

7.1.11. Novel techniques for linear arithmetic constraint solving

In [26], [27], we investigate new techniques for linear arithmetic constraint solving. They are based on the linear cube transformation, which allows us to efficiently determine whether a system of linear arithmetic constraints contains a hypercube of a given edge length.

Our first findings based on this transformation are two sound tests that find integer solutions for linear arithmetic constraints. While many complete methods search along the problem surface for a solution, these tests use cubes to explore the interior of the problems. The tests are especially efficient for constraints with a large number of integer solutions, e.g., those with infinite lattice width. Inside the SMT-LIB benchmarks, we have found almost one thousand problem instances with infinite lattice width. Experimental results confirm that our tests are superior on these instances compared to several state-of-the-art SMT solvers.

We also discovered that the linear cube transformation can be used to investigate the equalities implied by a system of linear arithmetic constraints. For this purpose, we developed a method that computes a basis for all implied equalities, i.e., a finite representation of all equalities implied by the linear arithmetic constraints. The equality basis can be used to decide whether a system of linear arithmetic constraints implies a given equality.

7.2. Formal Methods for Developing and Analyzing Algorithms and Systems

Participants: Noran Azmy, Gabriel Corona, Margaux Duroeulx, Marie Duflot-Kremer, Souad Kherroubi, Dominique Méry, Stephan Merz, Nicolas Schnepf, Christoph Weidenbach.

7.2.1. Making explicit domain knowledge in formal system development

Joint work with partners of the IMPEX project.

Modeling languages are concerned with providing techniques and tool support for the design, synthesis and analysis of the models resulting from a given modeling activity, and this activity is usually part of a system development model or process. These languages quite successfully focus on the analysis of the designed system, exploiting the semantic features of the underlying modeling language. These semantics are well understood by the system designers and/or the users of the modeling language, that is why we speak of implicit semantics.

In general, modeling languages are not equipped with resources, concepts or entities handling explicitly domain engineering features and characteristics (domain knowledge) in which the modeled systems evolve.

We posit that designers should explicitly handle the knowledge resulting from an analysis of the application domain, i.e. explicit semantics. As of today, making explicit the domain knowledge inside system design models does not follow any methodological rule; instead, features of domain knowledge are introduced in an ad-hoc way through types, constraints, profiles, etc.

Our claim [11] is that ontologies are good candidates for handling explicit domain knowledge. They define domain theories and provide resources for uniquely identifying concepts of domain knowledge. Therefore, allowing models to make references to ontologies is a modular solution for models to explicitly handle domain knowledge. Overcoming the absence of explicit semantics expression in the modeling languages used to specify systems models will increase the robustness of the designed system models. Indeed, references to the axioms and theorems resulting from the ontologies can be used to strengthen the properties of the designed models. The objective is to offer rigorous mechanisms for handling domain knowledge in design models. We also show how these mechanisms are set up in the cases of formal system models, both for static and dynamic aspects.

7.2.2. Incremental Development of Systems and Algorithms

Joint work with Andriamiarina, Manamiary Bruno, with Neeraj Kumar Singh from IRIT, Toulouse, with Rosemary Monahan, NUI Maynooth, Ireland, and with Zheng Cheng, LINA, Nantes.

The development of distributed algorithms and, more generally, of distributed systems, is a complex, delicate, and challenging process. The approach based on refinement applies a design methodology that starts from the most abstract model and leads, in an incremental way, to a distributed solution. The use of a proof assistant gives a formal guarantee on the conformance of each refinement with the model preceding it.

Our main results during 2016 are:

- An extension [18] for handling the verification of concurrent programs. In a second step, we show the importance of the concept of refinement, and how it can be used to found a methodology for designing concurrent programs using the coordination paradigm.
- A fully mechanized proof [36] of correctness of self-$*$ systems along with an interesting case study related to P2P-based self-healing protocols.
- We report on our progress in implementing a software development environment that integrates two formal software engineering techniques: program refinement as supported by Event-B, and program verification as supported by the Spec# programming system. We improve the usability of formal verification tools by providing a general framework for integrating these two approaches to software verification. We show how the two approaches, based respectively on correctness by construction and on post-hoc verification, can be used in a productive way. In [32], we focus on the final steps in this process where the final concrete specification is transformed into an executable algorithm.

We present EB2RC, a plug-in for the RODIN platform that reads in an Event-B model and uses the control framework introduced during its refinement to generate a graphical representation of the executable algorithm. EB2RC also generates a recursive algorithm that is easily translated into executable code. We illustrate our technique through case studies and their analysis.

7.2.3. Verification of the Pastry routing protocol

In her PhD thesis, Noran Azmy develops a formal proof in TLA$^+$ of the routing protocol used in the Pastry protocol [51] for maintaining a distributed hash table over a peer-to-peer network. In a previous thesis [47], Tianxiang Lu had found problems with all published versions of the original protocol, introduced a variant of Pastry, and given a first correctness proof of that protocol, assuming that no node ever disconnects. Due to limitations of TLAPS at that time, Lu's proof relied on many unchecked assumptions on arithmetic and on the underlying data structures, and it was later discovered that several of these assumptions were not valid.

Noran Azmy simplified the proof by introducing intermediate abstractions that allowed her to avoid low-level arithmetic reasoning in the main proof steps, and she proved lemmas corresponding to those assumptions that were actually used in the proof. As a result, she obtained a complete machine-checked proof of Lu's variant of the Pastry protocol, still under the assumption that no node leaves the network. Moreover, a close analysis of the invariant used in her simplified proof revealed that the protocol could be simplified by leaving out the final "lease exchange" protocol. The results were published at ABZ 2016 [22], and an extended article was invited for publication in Science of Computer Programming.

7.2.4. Proof of Determinacy of PharOS

Joint work with Selma Azaiez and Matthieu Lemerre (CEA Saclay), and Damien Doligez (Inria Paris).

As the main contribution of our group to the ADN4SE project funded by PIA, in cooperation with colleagues from CEA LIST, we wrote a high-level TLA$^+$ specification of the real-time operating system PharOS [46] and proved its executions to be deterministic. Roughly speaking, determinacy means that the sequence of local states of any process during a computation does not depend on the order in which processes are scheduled. The proof assumes that no deadlines are missed (which in practice is ensured by schedulability analysis of the particular applications). This property greatly simplifies the analysis and verification of programs that are executed within PharOS. The results were published at ABZ 2016 [21].

7.2.5. Formal Verification of Chains of Security Functions

Joint work with Rémi Badonnel and Abdelkader Lahmadi of the Madynes research group of Inria Nancy.

During his Master's thesis, Nicolas Schnepf studied formal techniques for the automatic verification of chains of security functions in a setting of software-defined networks (SDN). Concretely, he defined an extension of the Pyretic language [44] taking into account the data plane of SDN controllers and implemented a translation of that extension to the input languages of the nuXmv model checker and of SMT solvers. The approach and its scalability was validated over crafted security chains, and a conference paper describing the results is under preparation. Nicolas Schnepf started a PhD thesis in October 2016, jointly supervised by members of the Madynes and VeriDis groups.

7.2.6. Auditing hybrid systems for compliance

There is a huge gap in complexity between the actual analysis of a complex hybrid system and the analysis of the eventual control needed for safe operation. For example, for the combustion process of an engine there is not even a closed formal model, but the eventual control can be represented in a finite domain language. Such a language can then in particular be used for run-time control of a system through an auditor, providing the detection of faulty components or compliance violations. We have studied the consequences of such an approach if applied to the overall life time process of a technical system [29].

8. Bilateral Contracts and Grants with Industry

8.1. Modeling a Distributed File System

Participant: Stephan Merz.

Our group was contacted by Huawei R&D Silicon Valley for evaluating the suitability of using the TLA$^+$ specification language for describing high-level protocols used in Cloud systems. We provided a specification of protocols used in the Ceph file system [53]. We also provided on-site training for Huawei engineers in Chengdu, China.

8.2. Logic for Business

Participant:

The group in Saarbrücken has established a master agreement with L4B (Logic for Business) on the exchange of data and the creation of bilateral research projects. L4B is involved in several consulting projects with the German car industry on product specification strategies, including software.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. ANR-DFG Project SMArT

Participants: Haniel Barbosa, Pascal Fontaine, Marek Košta, Stephan Merz, Thomas Sturm.

The SMArT (Satisfiability Modulo Arithmetic Theories) project is funded by *ANR-DFG Programmes blancs 2013*, a program of the Agence Nationale de la Recherche and the (German) Deutsche Forschungsgemeinschaft DFG. It started in April 2014. The project gathers members of VeriDis in Nancy and Saarbrücken, and the Systerel company. The objective of the SMArT project is to provide advanced techniques for arithmetic reasoning beyond linear arithmetic for formal system verification, and particularly for SMT. The results feed back into the implementations of Redlog (section 6.2) and veriT (section 6.5), which also serve as experimentation platforms for theories, techniques and methods designed within this project.

More information on the project can be found on http://smart.gforge.inria.fr/.

9.1.2. ANR Project IMPEX

Participants: Souad Kherroubi, Dominique Méry.

The ANR Project IMPEX, within the INS program, started in December 2013 for 4 years. It is coordinated by Dominique Méry, the other partners are IRIT/ENSEIHT, Systerel, Supelec, and Telecom Sud Paris. The work reported here also included a cooperation with Pierre Castéran from LaBRI Bordeaux.

Modeling languages provide techniques and tool support for the design, synthesis, and analysis of the models resulting from a given modeling activity, as part of a system development process. These languages quite successfully focused on the analysis of the designed system exploiting the expressed semantic power of the underlying modeling language. The semantics of this modeling languages are well understood by the system designers and the users of the modeling language, i.e. the semantics is implicit in the model. In general, modeling languages are not equipped with resources, concepts or entities handling explicitly domain engineering features and characteristics (domain knowledge) underlying the modeled systems. Indeed, the designer has to explicitly handle the knowledge resulting from an analysis of this application domain [49], i.e. explicit semantics. Nowadays, making explicit the domain knowledge inside system design models does not obey any methodological rules validated by practice. The users of modeling languages introduce these domain knowledge features through types, constraints, profiles, etc. Our claim is that ontologies are good candidates for handling explicit domain knowledge. They define domain theories and provide resources for uniquely identifying domain knowledge concepts. Therefore, allowing models to make references to ontologies is a modular solution for models to explicitly handle domain knowledge. Overcoming the absence of explicit semantics expression in the modeling languages used to specify systems models will increase the robustness of the designed system models. Indeed, the axioms and theorems resulting from the ontologies can be used to strengthen the properties of the designed models. The objective [11] is to offer rigorous mechanisms for handling domain knowledge in design models.

9.1.3. Inria IPL HAC SPECIS

Participants: Marie Duflot-Kremer, Stephan Merz.

The goal of the HAC SPECIS (High-performance Application and Computers: Studying PErformance and Correctness In Simulation) project is to answer methodological needs of HPC application and runtime developers and to allow studying real HPC systems with respect to both correctness and performance. To this end, this Inria Project Lab assembles experts from the HPC, formal verification, and performance evaluation communities.

HAC SPECIS started in 2016. VeriDis contributes through its expertise in formal verification techniques. In particular, our goal is to extend the functionalities of exhaustive and statistical model checking within the SimGrid platform.

9.1.4. Inria Technological Development Action CUIC

Participants: Jasmin Christian Blanchette, Simon Cruanes.

Most “theorems” initially given to a proof assistant are incorrect, whether because of a typo, a missing assumption, or a fundamental flaw. Novices and experts alike can enter invalid formulas and find themselves wasting hours, or even days, on an impossible proof. This project, funded by Inria and running from 2015 to 2017, supports the development of a counterexample generator for higher-order logic. This new tool, called Nunchaku (cf. section 6.1), will be integrated in various proof assistants, including Isabelle, Coq, and the TLA$^+$ Proof System. The project is coordinated by Jasmin Blanchette and also involves Inria Saclay (Toccata group) and Inria Rennes (Celtique group), among others. Simon Cruanes was hired in October 2015 and has started the development of Nunchaku, whereas Blanchette has developed an Isabelle frontend. Three releases have taken place so far, and the tool is an integral part of the Isabelle2016-1 official release. Work has started on Coq and TLAPS frontends. The tool is described in a conference publication [33] and was presented at a workshop [28].

9.1.5. Inria ADT PLM (2014-2016)

Participant: Matthieu Nicolas.

Joint work with Gérald Oster (project-team Coast, Inria Nancy – Grand Est) and Martin Quinson (project-team Myriads, Inria Rennes – Bretagne Atlantique)

The goal of this project is to establish an experimental platform for studying the didactics of informatics, specifically centered on introductory programming courses.

The project builds upon a pedagogical platform for supervising programming exercises developed for our own teaching, and improves this base in several ways. We want to provide more adapted feedback to the learners, and gather more data to better understand how beginners learn programming.

This year, we finalized the web version of our framework, and submitted several project applications to pursue this work in the future. Unfortunately, none of these applications have been accepted so far. Martin Quinson invited Peter Hubwieser, professor of the Technical University of Munich (TUM) and specialist of the didactics of Computer Science, for two weeks in November. Developing the PLM and exploiting the data already gathered were central elements of this work meeting. A joint publication is currently prepared, targeting the ItiCSE'17 conference.

9.2. European Initiatives

9.2.1. FP7 & H2020 Projects

Program: H2020-FETOPEN-2015-CSA

Project acronym: SC^2

Project title: Satisfiability Checking and Symbolic Computation

Duration: July 2016 – September 2018

Coordinator: James H. Davenport (U. Bath, U.K.)

Other partners: RWTH Aachen (Germany), Fondazione Bruno Kessler (Italy), Università degli Studi di Genova (Italy), Maplesoft Europe Ltd (Germany), Coventry University (U.K.), University of Oxford (U.K.), Universität Kassel (Germany), Max Planck Institut für Informatik (Germany), Universität Linz (Austria)

Abstract: Whereas symbolic computation is concerned with efficient algorithms for determining exact solutions to complex mathematical problems, more recent developments in the area of satisfiability checking tackle similar problems with different algorithmic and technological solutions. Both communities have made remarkable progress in the last decades and address practical problems of rapidly increasing size and complexity. For example, satisfiability checking is an essential backend for assuring the security and the safety of computer systems. Techniques and tools of symbolic computation are used by different scientific communities for solving large mathematical problems that are out of reach of pencil and paper developments. Currently the two communities are largely disjoint and unaware of the achievements of each other, despite strong reasons for them to discuss and collaborate, as they share many central interests. Bridges between the communities in the form of common platforms and roadmaps are necessary to initiate an exchange, and to support and to direct their interaction. This Coordination and Support Action within the FET-Open framework will initiate a wide range of activities to bring the two communities together, identify common challenges, offer global events and bilateral visits, propose standards, and so on. Combining the knowledge, experience and the technologies in these communities will lead to cross-fertilization and mutual improvements, enabling the development of radically improved software tools.

9.3. International Initiatives

9.3.1. Inria International Partners

9.3.1.1. KANASA

Title: Kanazawa-Nancy for Satistifiability and Arithmetics

International Partner: Japan Advanced Institute for Science and Technology (Dept. Intelligent Robotics, Mizuhito Ogawa)

Starting year: 2016

During the last decade, there has been tremendous progress on symbolic verification techniques, spurred in particular by the development of SMT (satisfiability modulo theories) techniques and tools. Our first direction of research will be to investigate the theoretical background and the practical techniques to integrate Interval Constraint Propagation within a generic SMT framework, including other decision procedures and quantifier handling techniques. On the purely arithmetic side, we also want to study how to unite the reasoning power of all arithmetic techniques developed in the team, including simplex-based SMT-like reasoners, Virtual Substitution, and Cylindrical Algebraic Decomposition. In particular, this includes developing theory combination frameworks for linear and non-linear arithmetic. There is a strong incentive for these kind of combinations since even non-linear SMT problems contain a large proportion of linear constraints. The partnership is supported by a Memorandum of Understanding between JAIST and LORIA.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

Ilina Stoilkovska

Date: 1 September – 31 October

Institution: TU Wien (Austria)

Host: Stephan Merz

Ilina is a PhD student at TU Wien, Austria, and works on tailored abstractions for the parameterized verification of fault-tolerant distributed algorithms. During her stay in Nancy, she worked on a formal soundness proof of her abstractions in the TLA$^+$ Proof System.

Tung Vu Xuan

Date: 1 May 2016 – 30 April 2017

Institution: JAIST

Host: Pascal Fontaine

Tung Vu Xuan is a PhD student at JAIST, Japan. He is visiting VeriDis in the context of the KANASA project. He works mainly on Interval Constraint Propagation (ICP), a heuristic but powerful method for satisfiability checking of non-linear arithmetic (NLA) constraints. During his stay, we investigate techniques to combine ICP with decision procedures for NLA within an SMT context.

9.4.2. Internships

Anders Olav Candasamy

Date: 1 March – 31 July

Institution: Université de Lorraine (Erasmus Mundus DESEM)

Host: Dominique Méry

Anders Candasamy analyzed a hemodialysis case study using Event-B. Besides developing the formal model, he also reflected on the modeling process and proposed several methodological improvements.

Matthieu Lequesne

Date: 1 March – 31 July

Institution: École Polytechnique

Host: Stephan Merz

Matthieu Lequesne worked on translating formulas in a core sublanguage of TLA$^+$ to the input format of Nunchaku (section 6.1), with the aim of producing (counter)models for TLA$^+$ proof obligations.

Weichung Shaw

Date: 1 March – 31 August

Institution: Université de Lorraine (Erasmus Mundus DESEM)

Host: Stephan Merz

Weichung Shaw worked on formalizing a correctness proof of the Raft consensus algorithm [50] in TLA$^+$. He proved several fundamental lemmas and documented several methodological issues with the use of TLAPS.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Organization of Scientific Events

10.1.1.1. General Chair, Scientific Chair

Jasmin Blanchette and Stephan Merz, with the help of Anne-Lise Charbonnier of Inria Nancy, organized the *7th International Conference on Interactive Theorem Proving* (ITP 2016) and associated workshops in Nancy, on August 22–27, 2016.

10.1.1.2. Member of the Organizing Committees

Jasmin Blanchette co-organized the *Hammers for Type Theories* (HaTT 2016) workshop at IJCAR 2016 in Coimbra, Portugal.

Pascal Fontaine co-organized the *First SC^2 workshop on Satisfiability Checking and Symbolic Computation* with Erika Abraham (RWTH, Aachen).

Pascal Fontaine co-organized the 5th Workshop on Practical Aspects of Automated Reasoning (PAAR) with Stephan Schulz (DHBW Stuttgart) and Josef Urban (Czech Technical University in Prague).

Dominique Méry was a member of the organizing committees of the workshops F-IDE, BWare, Impex, and Formose.

Dominique Méry, together with Yamine Aït-Ameur (Toulouse) and Shin Nakajima (Tokyo), organized a meeting on *Implicit and explicit semantics integration in proof based developments of discrete systems* in November within the series of NII Shonan meetings.

The International Summer School on Verification Techniques, Systems, and Applications (VTSA) has been organized since 2008 in the Greater Region (Nancy, Saarbrücken, Luxembourg, Liège, and Koblenz), and Stephan Merz and Christoph Weidenbach are co-organizers of VTSA. In 2016, VTSA took place at the end of August in Liège, Belgium.

10.1.2. Selection of Scientific Events

10.1.2.1. Chair of Conference Program Committees

Jasmin Blanchette and Stephan Merz chaired the program committee of the *7th International Conference on Interactive Theorem Proving* (ITP 2016).

Stephan Merz co-chaired the program committee of the Third International Workshop on Formal Reasoning in Distributed Algorithms (FRiDA), organized in May as a satellite of NETYS in Marrakech, Morocco.

10.1.2.2. Member of Conference Program Committees

Jasmin Blanchette served on the program committee of the *International Conference on Tests and Proofs* (TAP).

Pascal Fontaine served on the program committee of the workshop SMT.

Stephan Merz served on the program committees of the international conferences ABZ, ICALP, and ICFEM, and of the workshops ARQNL, FMICS-AVoCS, and GRSRD.

Martin Strecker served on the program committees of ICTERI and ICGT.

Thomas Sturm served on the program committees of CASC and of the SC^2 workshop at SYNACS.

Uwe Waldmann served on the program committee of the workshop PAAR, colocated with IJCAR 2016.

Christoph Weidenbach served on the program committee of IJCAR.

10.1.3. Journals

Stephan Merz, together with Jun Pang of the University of Luxembourg, edited two volumes of a special issue on Formal Engineering Methods in the journal *Formal Aspects of Computing*.

Thomas Sturm is a member of the editorial boards of the *Journal of Symbolic Computation* (Elsevier) and *Mathematics in Computer Science* (Springer).

Christoph Weidenbach is an editor of the Journal of Automated Reasoning. Together with Deepak Kapur and Stéphane Demri he edited a special issue of JAR containing selected and extended papers of IJCAR 2014.

10.1.4. Invited Talks

Jasmin Blanchette gave invited talks at the Semantic Representation of Mathematical Knowledge Workshop organized by the Wolfram Foundation and the Fields Institute in Toronto, Canada, at the Sino-German Frontiers of Science Symposium (SINOGFOS) organized by the Humboldt Foundation and the Chinese Academy of Science in Shenzhen, China, at the Workshop on Proofs, Justifications, and Certificates in Toulouse, France, at the Universality of Proof seminar at Schloss Dagstuhl in Wadern, Germany, and at the Prague Inter-Reasonning Workshop (PIWo) in Prague, Czech Republic.

Pascal Fontaine gave an invited talk at the AFSEC day of the GdR GPL, and at GT-Verif day of the GdR IM.

Stephan Merz gave invited talks at the TRS meeting and the JAIST-LORIA workshop in Kanazawa, Japan, on *Satisfiability Checking for Modal Logics via SMT Solving* and on *The Design of the TLA$^+$ Proof System*. He also gave an invited talk at the *Cloud Reliability Workshop* in Shenzhen, China, on *A Formal Analysis of Pastry*.

Thomas Sturm gave an invited talk at ACA 2016 titled *Real Problems over the Reals*.

Christoph Weidenbach gave an invited lecture at the SMT Summer School in Lisbon, Portugal.

10.1.5. Leadership within the Scientific Community

Jasmin Blanchette served as editor of the newsletter of the Association for Automated Reasoning (AAR) and as member of the AAR board.

Jasmin Blanchette and Christoph Weidenbach were elected on the CADE (*Conference on Automated Deduction*) Inc. Board of Trustees. Christoph Weidenbach was elected President of CADE Inc. by the CADE Inc. Board of Trustees.

Jasmin Blanchette is an ex officio member of the steering committee of the conference series *Interactive Theorem Proving*.

Pascal Fontaine is an SMT-LIB manager, together with Clark Barrett (Stanford University) and Cesare Tinelli (University of Iowa). He is a member of the FroCoS steering Committee. He has been an elected CADE trustee since October 2014. He serves as member of the Association for Automated Reasoning (AAR) board.

Stephan Merz is a member of the IFIP Working Group 2.2 on *Formal Description of Programming Concepts*. He is also a member of the steering committee of the workshop on Automated Verification of Critical Systems (AVoCS).

Thomas Sturm is a member of the steering committee of the conference series *Mathematical Aspects of Computer and Information Sciences* (MACIS).

Christoph Weidenbach is a member of the steering committee of IJCAR.

10.1.6. Scientific Expertise

Pascal Fontaine was a panel member for the CASC-25 competition of first-order theorem prover.

Stephan Merz served as an expert for the French Agence Nationale de la Recherche (ANR), the Haut Conseil de l'Évaluation de la Recherche et de l'Enseignement Supérieur (HCERES), and for the European Research Council (ERC).

Christoph Weidenbach served as an expert for GIF (German Israel Foundation), the FWF (Austrian Science Fund) and the DFG (German Science Foundation).

10.1.7. Research Administration

Dominique Méry is the head of the Doctoral School IAEM Lorraine for the University of Lorraine.

Stephan Merz is a member of the Scientific Directorate of the International Computer Science Meeting Center in Schloss Dagstuhl. Until August 2016, he was the head of the PhD committee for computer science of the Doctoral School IAEM Lorraine. Since September 2016, he is the delegate for scientific affairs at the Inria Nancy – Grand Est research center. He is also the delegate for the organization of conferences at Inria Nancy and the coordinator of the CPER *Sciences du Numérique* in Lorraine (2015–2020). He was a member of the hiring committee of junior researchers at Inria Nancy in 2016 and a member of the committee for the SIF thesis award (*Prix Gilles Kahn*).

Christoph Weidenbach is a member of the selection committee of the Saarbrücken Graduate School in Computer Science.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Master: Jasmin Blanchette, Computational Metaphysics (guest lecturer), 4 HETD, Freie Universität Berlin, Germany.

Licence: Marie Duflot-Kremer, Algorithmique et Programmation 1, 80 HETD L1 Mathématiques, Informatiques Sciences pour l'Ingénieur, Université de Lorraine, France.

Licence: Marie Duflot-Kremer, Bases de données 1 et 2, 35 HETD, L2 informatique, Université de Lorraine, France.

Licence: Marie Duflot-Kremer, Projet personnel et communication, 50 HETD, L2 informatique, Université de Lorraine, France.

Master : Marie Duflot-Kremer, Vérification de systèmes, 30 HETD, M1 Informatique, Université de Lorraine, France.

Master: Marie Duflot-Kremer and Stephan Merz, Vérification algorithmique, 30 HETD, M2 Informatique, Université de Lorraine, France.

Master: Marie Duflot-Kremer and Stephan Merz, Elements of Model Checking, 36 HETD, M2 Informatique and Master Erasmus Mundus DESEM, Université de Lorraine, France.

Master : Marie Duflot-Kremer and Stephan Merz, Conception et architectures distribuées 24 HETD M1 informatique, Université de Lorraine

Licence : Pascal Fontaine, Structure des ordinateurs, 67 HETD, L2 MIASHS, parcours MIAGE, Université de Lorraine, France.

Licence : Pascal Fontaine, Logique des prédicats, 32 HETD, L2 MIASHS, Université de Lorraine, France.

Master : Pascal Fontaine, Réseaux, 50 HETD, M1 MIAGE, Université de Lorraine, France.

Master : Pascal Fontaine, Génie Logiciel, 30 HETD, M1 MIAGE, IGA Rabbat et Université de Lorraine, Maroc.

Master: Dominique Méry, Models and algorithms, 60 HETD, M1, Telecom Nancy, Université de Lorraine, France.

Master: Dominique Méry, Formal model engineering, 24 HETD, M2, Telecom Nancy, Université de Lorraine, France.

Master: Dominique Méry, Modeling Systems, 30 HETD, M2, Telecom Nancy, Université de Lorraine, France.

Master: Dominique Méry, Modeling Systems, 36 HETD, M2 informatique and Master Erasmus Mundus DESEM, Université de Lorraine, France.

Master: Dominique Méry, Event-B modeling, 8 HETD, NUI Maynooth.

Master: Uwe Waldmann, Automated Reasoning I, 90 HETD, Universität des Saarlandes, Germany.

Master: Uwe Waldmann, Automated Reasoning II, 60 HETD, Universität des Saarlandes, Germany. This lecture received the teaching award of the Computer Science Students Association.

10.2.2. Supervision

PhD: Noran Azmy, An Automated Proof of Correctness for Pastry, Saarland University and Université de Lorraine, defended on November 24, 2016.

PhD: Marek Košta, Computational Logic, Universität des Saarlandes. Defended on December 13, 2016.

PhD in progress: Gabor Alági, Efficient Reasoning in Finite Domains, Saarland University. Supervised by Christoph Weidenbach, since 11/2012.

PhD in progress: Haniel Barbosa, Refutational Completeness in Satisfiability Modulo Theories, Université de Lorraine and UFRN (Natal, Brazil). Supervised by David Déharbe, Pascal Fontaine, and Stephan Merz, since 12/2013.

PhD in progress: Martin Bromberger, Arithmetic Reasoning, Saarland University. Supervised by Christoph Weidenbach, since 07/2014.

PhD in progress: Mathias Fleury, Formalization of Logical Calculi, Saarland University. Supervised by Christoph Weidenbach and Jasmin Blanchette, since 09/2015.

PhD in progress: Marco Voigt, Decidable Hierarchic Combinations, Saarland University. Supervised by Christoph Weidenbach, since 11/2013.

PhD in progress: Daniel Wand, First-Order Extensions to Support Higher-Order Reasoning, Saarland University. Supervised by Christoph Weidenbach and Jasmin Blanchette, since 02/2011.

10.2.3. Thesis committees

Dominique Méry served on the committees for the PhD thesis of Pierre Halmagrand (CNAM) and the habilitation thesis of Brahim Hamid (Université Toulouse Jean Jaurès).

Stephan Merz served as a reviewer for the PhD thesis of Yakoub Némouchi (Université Paris Saclay) and as a PhD examiner for the PhD thesis of Alland Blanchard (Université d'Orléans).

10.3. Science outreach

Marie Duflot-Kremer took part in various science outreach activities, with a public ranging from primary school kids to golden agers, including high school and potential university students. A selection of these activities is given below:

- two days at "Fête de la science" in Nancy (Faculté de Sciences et Technologies and ARTEM);
- a course on Scratch for high school professors in charge of teaching optional course ISN (Informatique et Sciences du Numérique);
- her explanations of three new unplugged activities (data bases, model checking and text compression) have been recorded by Inria and will soon be added to the Youtube channel of Interstice intended for promoting and sharing such activities;
- she is in charge of the scientific part of the second module in the Class'Code project, aiming at training teachers and educators for carrying out computer science activities with childrens aged 8 to 14 years;
- she is a member of two groups including university and secondary school teachers, dedicated to the training of math teachers who now teach computer science to students of age 11 to 18. A day of training was given to high school teachers;
- "Journée femmes de Sciences": one day dedicated to the promotion of science towards 14 year-old girls;

- she is a member of the steering committee preparing an itinerant exposition intended for explaining computer science to the public, to be released in December 2016;
- she presented unplugged outreach activities to the staff at Cité des Sciences (Paris);
- she conducted during five months an experiment on the discovery of programming for golden agers using Scratch;
- she took part in “Pépinière 4.0” and 4.1, explaining computer science concepts to teachers.

11. Bibliography

Major publications by the team in recent years

[1] T. BOUTON, D. C. B. DE OLIVEIRA, D. DÉHARBE, P. FONTAINE.*veriT: an open, trustable and efficient SMT-solver*, in "Proc. Conference on Automated Deduction (CADE)", Montreal, Canada, R. SCHMIDT (editor), Lecture Notes in Computer Science, Springer, 2009, vol. 5663, p. 151-156.

[2] D. CANSELL, D. MÉRY.*The Event-B Modelling Method: Concepts and Case Studies*, in "Logics of Specification Languages", Berlin-Heidelberg, D. BJØRNER, M. C. HENSON (editors), Monographs in Theoretical Computer Science, Springer, 2008, p. 47-152.

[3] D. COUSINEAU, D. DOLIGEZ, L. LAMPORT, S. MERZ, D. RICKETTS, H. VANZETTO.*TLA+ Proofs*, in "18th International Symposium On Formal Methods - FM 2012", Paris, France, D. GIANNAKOPOULOU, D. MÉRY (editors), Lecture Notes in Computer Science, Springer, 2012, vol. 7436, p. 147-154.

[4] A. DOLZMANN, T. STURM.*Redlog: Computer algebra meets computer logic*, in "ACM SIGSAM Bull.", 1997, vol. 31, n^{o} 2, p. 2-9.

[5] D. DÉHARBE, P. FONTAINE, S. MERZ, B. WOLTZENLOGEL PALEO.*Exploiting Symmetry in SMT Problems*, in "23rd Intl. Conf. Automated Deduction (CADE 2011)", Wroclaw, Poland, N. BJØRNER, V. SOFRONIE-STOKKERMANS (editors), LNCS, Springer, 2011, vol. 6803, p. 222-236.

[6] A. FIETZKE, C. WEIDENBACH.*Superposition as a Decision Procedure for Timed Automata*, in "Mathematics in Computer Science", 2012, vol. 6, n^{o} 4, p. 409-425.

[7] E. KRUGLOV, C. WEIDENBACH.*Superposition Decides the First-Order Logic Fragment Over Ground Theories*, in "Mathematics in Computer Science", 2012, vol. 6, n^{o} 4, p. 427-456.

[8] F. KRÖGER, S. MERZ.*Temporal Logic and State Systems*, Texts in Theoretical Computer Science, Springer, 2008, 436, http://hal.inria.fr/inria-00274806/en/.

[9] S. MERZ.*The Specification Language TLA^{+}*, in "Logics of Specification Languages", Berlin-Heidelberg, D. BJØRNER, M. C. HENSON (editors), Monographs in Theoretical Computer Science, Springer, 2008, p. 401-451.

[10] C. WEIDENBACH, D. DIMOVA, A. FIETZKE, M. SUDA, P. WISCHNEWSKI.*SPASS Version 3.5*, in "22nd International Conference on Automated Deduction (CADE-22)", Montreal, Canada, R. SCHMIDT (editor), LNAI, Springer, 2009, vol. 5663, p. 140-145.

Publications of the year

Articles in International Peer-Reviewed Journal

[11] Y. AIT AMEUR, D. MÉRY. *Making explicit domain knowledge in formal system development*, in "Science of Computer Programming", March 2016, vol. 121, n^{o} 100–127 [*DOI :* 10.1016/J.SCICO.2015.12.004], https://hal.inria.fr/hal-01245832.

[12] J. C. BLANCHETTE, S. BÖHME, M. FLEURY, S. J. SMOLKA, A. STECKERMEIER. *Semi-intelligible Isar Proofs from Machine-Generated Proofs*, in "Journal of Automated Reasoning", 2016 [*DOI :* 10.1007/S10817-015-9335-3], https://hal.inria.fr/hal-01211748.

[13] J. C. BLANCHETTE, D. GREENAWAY, C. KALISZYK, D. KÜHLWEIN, J. URBAN. *A Learning-Based Fact Selector for Isabelle/HOL*, in "Journal of Automated Reasoning", 2016, vol. 57, p. 219 - 244 [*DOI :* 10.1007/S10817-016-9362-8], https://hal.inria.fr/hal-01386986.

[14] J. C. BLANCHETTE, C. KALISZYK, L. C. PAULSON, J. URBAN. *Hammering towards QED*, in "Journal of Formalized Reasoning", 2016, vol. 9, n^{o} 1, p. 101-148, https://hal.inria.fr/hal-01386988.

[15] M. KOŠTA, T. STURM, A. DOLZMANN. *Better answers to real questions*, in "Journal of Symbolic Computation", 2016, vol. 74, p. 255 - 275 [*DOI :* 10.1016/J.JSC.2015.07.002], https://hal.inria.fr/hal-01388720.

[16] S. MERZ, J. PANG. *Editorial*, in "Formal Aspects of Computing", 2016, vol. 28, n^{o} 3, p. 343-344 [*DOI :* 10.1007/S00165-016-0390-2], https://hal.inria.fr/hal-01356470.

[17] S. MERZ, J. PANG. *Editorial*, in "Formal Aspects of Computing", 2016, vol. 28, n^{o} 5, p. 723-724 [*DOI :* 10.1007/S00165-016-0390-2], https://hal.inria.fr/hal-01356471.

[18] D. MÉRY. *Playing with State-Based Models for Designing Better Algorithms*, in "Future Generation Computer Systems", May 2016, 25, https://hal.inria.fr/hal-01316026.

Invited Conferences

[19] *Best Paper*
A. REYNOLDS, J. C. BLANCHETTE. *A Decision Procedure for (Co)datatypes in SMT Solvers*, in "IJCAI 2016", New York City, United States, Proceedings of the Twenty-Fifth International Joint Conference on Artificial Intelligence, IJCAI 2016, New York, NY, USA, 9-15 July 2016, July 2016, https://hal.inria.fr/hal-01397082.

International Conferences with Proceedings

[20] E. H. ABRAHÁM, J. ABBOTT, B. BECKER, A. M. BIGATTI, M. M. BRAIN, B. BUCHBERGER, A. CIMATTI, J. H. DAVENPORT, M. M. ENGLAND, P. FONTAINE, S. M. FORREST, A. GRIGGIO, D. KROENING, W. M. SEILER, T. STURM. *SC 2 : Satisfiability Checking meets Symbolic Computation (Project Paper)*, in "Intelligent Computer Mathematics", Bialystok, Poland, July 2016, https://hal.inria.fr/hal-01377655.

[21] S. AZAIEZ, D. DOLIGEZ, M. LEMERRE, T. LIBAL, S. MERZ. *Proving Determinacy of the PharOS Real-Time Operating System*, in "Abstract State Machines, Alloy, B, TLA, VDM, and Z - 5th International Conference, ABZ 2016", Linz, Austria, M. J. BUTLER, K.-D. SCHEWE, A. MASHKOOR, M. BIRÓ (editors), LNCS -

Lecture Notes in Computer Science, Springer, May 2016, vol. 9675, p. 70-85 [*DOI :* 10.1007/978-3-319-33600-8_4], https://hal.inria.fr/hal-01322335.

[22] N. AZMY, S. MERZ, C. WEIDENBACH.*A Rigorous Correctness Proof for Pastry*, in "Abstract State Machines, Alloy, B, TLA, VDM, and Z - 5th International Conference, ABZ 2016", Linz, Austria, M. J. BUTLER, K.-D. SCHEWE, A. MASHKOOR, M. BIRÓ (editors), Springer, 2016, vol. 9675, p. 86-101 [*DOI :* 10.1007/978-3-319-33600-8_5], https://hal.inria.fr/hal-01322342.

[23] J. C. BLANCHETTE, A. BOUZY, A. LOCHBIHLER, A. POPESCU, D. TRAYTEL.*Friends with Benefits: Implementing Foundational Corecursion in Isabelle/HOL (Extended Abstract)*, in "Isabelle Workshop 2016", Nancy, France, August 2016, https://hal.inria.fr/hal-01401812.

[24] J. C. BLANCHETTE, M. FLEURY, C. WEIDENBACH.*A Verified SAT Solver Framework with Learn, Forget, Restart, and Incrementality (Extended Abstract)*, in "Isabellle Workshop 2016", Nancy, France, August 2016, https://hal.inria.fr/hal-01401807.

[25] *Best Paper*
J. C. BLANCHETTE, M. FLEURY, C. WEIDENBACH.*A Verified SAT Solver Framework with Learn, Forget, Restart, and Incrementality*, in "8th International Joint Conference on Automated Reasoning (IJCAR 2016)", Coimbra, Portugal, Automated Reasoning - 8th International Joint Conference, IJCAR 2016, Coimbra, Portugal, June 27 - July 2, 2016, Proceedings, June 2016 [*DOI :* 10.1007/978-3-319-40229-1_4], https://hal.inria.fr/hal-01336074.

[26] M. BROMBERGER, C. WEIDENBACH.*Computing a Complete Basis for Equalities Implied by a System of LRA Constraints*, in "14th International Workshop on Satisfiability Modulo Theories", Coimbra, Portugal, T. KING, R. PISKAC (editors), CEUR Workshop Proceedings, 2016, vol. 1617, p. 15-30, https://hal.inria.fr/hal-01403214.

[27] M. BROMBERGER, C. WEIDENBACH.*Fast Cube Tests for LIA Constraint Solving*, in "Automated Reasoning - 8th International Joint Conference (IJCAR 2016)", Coimbra, Portugal, N. OLIVETTI, A. TIWARI (editors), Lecture Notes in Computer Science, Springer, 2016, vol. 9706, p. 116-132 [*DOI :* 10.1007/978-3-319-40229-1_9], https://hal.inria.fr/hal-01403200.

[28] S. CRUANES, J. C. BLANCHETTE.*Extending Nunchaku to Dependent Type Theory*, in "Hammers for Type Theories (HaTT 2016)", Coimbra, Portugal, Proceedings First International Workshop on Hammers for Type Theories, July 2016, vol. 210, p. 3 - 12 [*DOI :* 10.4204/EPTCS.210.3], https://hal.inria.fr/hal-01401696.

[29] C. FETZER, C. WEIDENBACH, P. WISCHNEWSKI.*Compliance, Functional Safety and Fault Detection by Formal Methods*, in "Leveraging Applications of Formal Methods, Verification and Validation (ISOLA 2016)", Corfu, Greece, T. MARGARIA, B. STEFFEN (editors), Lecture Notes in Computer Science, Springer, 2016, vol. 9953, p. 626 - 632 [*DOI :* 10.1007/978-3-319-47169-3_48], https://hal.inria.fr/hal-01403190.

[30] J. HAËL BRENAS, R. ECHAHED, M. STRECKER.*Ensuring Correctness of Model Transformations While Remaining Decidable*, in "Theoretical Aspects of Computing - ICTAC", Taipei, Taiwan, Theoretical Aspects of Computing – ICTAC 2016 13th International Colloquium, Taipei, Taiwan, ROC, October 24–31, 2016, Proceedings, October 2016, p. 315 - 332 [*DOI :* 10.1007/978-3-319-46750-4_18], https://hal.archives-ouvertes.fr/hal-01403585.

[31] S. MERZ, H. VANZETTO.*Encoding TLA+ into Many-Sorted First-Order Logic*, in "Abstract State Machines, Alloy, B, TLA, VDM, and Z - 5th International Conference, ABZ 2016", Linz, Austria, M. J. BUTLER, K.-D. SCHEWE, A. MASHKOOR, M. BIRÓ (editors), Springer, 2016, vol. 9675, p. 54-69 [*DOI :* 10.1007/978-3-319-33600-8_3], https://hal.inria.fr/hal-01322328.

[32] D. MÉRY, R. MONAHAN, C. ZHENG.*On two Friends for getting Correct ProgramsAutomatically Translating Event B Specifications to Recursive Algorithms in Rodin*, in "ISOLA 2016", CORFU, Greece, B. STEFFEN, T. MARGARIA (editors), Leveraging Applications of Formal Methods, Verification and Validation: Foundational Techniques, Springer, October 2016, vol. I, n^{o} 9952, 18 [*DOI :* 10.1007/978-3-319-47166-2_57], https://hal.inria.fr/hal-01369425.

[33] A. REYNOLDS, J. C. BLANCHETTE, S. CRUANES, C. TINELLI.*Model Finding for Recursive Functions in SMT*, in "8th International Joint Conference on Automated Reasoning (IJCAR 2016)", Coimbra, Portugal, Automated Reasoning - 8th International Joint Conference, IJCAR 2016, Coimbra, Portugal, June 27 - July 2, 2016, Proceedings, June 2016 [*DOI :* 10.1007/978-3-319-40229-1_10], https://hal.inria.fr/hal-01336082.

[34] T. STURM, M. VOIGT, C. WEIDENBACH.*Deciding First-Order Satisfiability when Universal and Existential Variables are Separated*, in "LICS 2016", New York, United States, July 2016, p. 86 - 95 [*DOI :* 10.1145/2933575.2934532], https://hal.inria.fr/hal-01389744.

[35] A. TEUCKE, C. WEIDENBACH.*Ordered Resolution with Straight Dismatching Constraints*, in "5th Workshop on Practical Aspects of Automated Reasoning (PAAR 2016)", Coimbra, Portugal, P. FONTAINE, S. SCHULZ, J. URBAN (editors), CEUR Workshop Proceedings, 2016, vol. 1635, p. 95-109, https://hal.inria.fr/hal-01403206.

Scientific Books (or Scientific Book chapters)

[36] M. B. ANDRIAMIARINA, D. MÉRY, N. K. SINGH.*Incremental Proof-Based Development for Resilient Distributed Systems*, in "Trustworthy Cyber-Physical Systems Engineering", Trustworthy Cyber-Physical Systems Engineering, Taylor and Francis Group, September 2016, https://hal.archives-ouvertes.fr/hal-01246669.

Books or Proceedings Editing

[37] J. C. BLANCHETTE, S. MERZ (editors). *Interactive Theorem Proving: 7th International Conference, ITP 2016*, Lecture Notes in Computer Science, Springer, Nancy, France, 2016, vol. 9807 [*DOI :* 10.1007/978-3-319-43144-4], https://hal.inria.fr/hal-01356464.

References in notes

[38] J.-R. ABRIAL.*Modeling in Event-B: System and Software Engineering*, Cambridge University Press, 2010.

[39] L. BACHMAIR, H. GANZINGER.*Rewrite-Based Equational Theorem Proving with Selection and Simplification*, in "Journal of Logic and Computation", 1994, vol. 4, n^{o} 3, p. 217–247.

[40] R. BACK, J. VON WRIGHT.*Refinement calculus—A systematic introduction*, Springer Verlag, 1998.

[41] C. BARRETT, R. SEBASTIANI, S. A. SESHIA, C. TINELLI.*Satisfiability Modulo Theories*, in "Handbook of Satisfiability", A. BIERE, MARIJN J. H. HEULE, H. VAN MAAREN, T. WALSH (editors), Frontiers in Artificial Intelligence and Applications, IOS Press, February 2009, vol. 185, chap. 26, p. 825-885.

[42] P. CHOCRON, P. FONTAINE, C. RINGEISSEN.*A Polite Non-Disjoint Combination Method: Theories with Bridging Functions Revisited*, in "25th International Conference on Automated Deduction, CADE-25", Berlin, Germany, A. P. FELTY, A. MIDDELDORP (editors), Lecture Notes in Computer Science, Springer, August 2015, vol. 9195, p. 419-433 [*DOI :* 10.1007/978-3-319-21401-6_29], https://hal.inria.fr/hal-01157898.

[43] P. CHOCRON, P. FONTAINE, C. RINGEISSEN.*A Rewriting Approach to the Combination of Data Structures with Bridging Theories*, in "Frontiers of Combining Systems - 10th International Symposium, FroCoS 2015", Wroclaw, Poland, C. LUTZ, S. RANISE (editors), Lecture Notes in Computer Science, Springer, September 2015, vol. 9322, p. 275–290 [*DOI :* 10.1007/978-3-319-24246-0_17], https://hal.inria.fr/hal-01206187.

[44] N. FOSTER, A. GUHA, M. REITBLATT, A. STORY, M. J. FREEDMAN, N. PRAVEEN KATTA, C. MONSANTO, J. REICH, J. REXFORD, C. SCHLESINGER, D. WALKER, R. HARRISON.*Languages for software-defined networks*, in "IEEE Communications Magazine", 2013, vol. 51, n^{o} 2, p. 128-134.

[45] L. LAMPORT.*Specifying Systems*, Addison-Wesley, Boston, Mass., 2002.

[46] M. LEMERRE, E. OHAYON.*A Model of Parallel Deterministic Real-Time Computation*, in "Proc. 33rd IEEE Real-Time Systems Symposium (RTSS 2012)", San Juan, PR, U.S.A., IEEE Comp. Soc., 2012, p. 273-282.

[47] T. LU.*Formal Verification of the Pastry Protocol*, Universität des Saarlandes and Université de Lorraine, 2013.

[48] C. MORGAN.*Programming from Specifications*, Prentice Hall, 1998, 2nd edition.

[49] D. MÉRY, S. RUSHIKESH, A. TARASYUK.*Integrating Domain-Based Features into Event-B: a Nose Gear Velocity Case Study*, in "Model and Data Engineering - 5th International Conference, MEDI 2015", Rhodos, Greece, L. BELLATRECHE, Y. MANOLOPOULOS (editors), LNCS, Springer, 2015, vol. 9344, p. 89-102, https://hal.inria.fr/hal-01245991.

[50] D. ONGARO, J. K. OUSTERHOUT.*In Search of an Understandable Consensus Algorithm*, in "USENIX Annual Technical Conference 2014", Philadelphia, PA, G. GIBSON, N. ZELDOVICH (editors), Usenix Association, 2014, p. 305-319.

[51] A. ROWSTRON, P. DRUSCHEL.*Pastry: Scalable, Decentralized Object Location, and Routing for Large-Scale Peer-to-Peer Systems*, in "IFIP/ACM International Conference on Distributed Systems Platforms (Middleware 2001)", Heidelberg, Germany, R. GUERRAOUI (editor), Lecture Notes in Computer Science, Springer, 2001, vol. 2218, p. 329-350.

[52] V. SOFRONIE-STOKKERMANS.*Hierarchical and modular reasoning in complex theories: The case of local theory extensions*, in "Frontiers of Combining Systems. 6th International Symposium FroCos 2007, Proceedings", Liverpool, UK, B. KONEV, F. WOLTER (editors), Lecture Notes in Computer Science, Springer, 2007, vol. 4720, p. 47-71, Invited paper.

[53] S. A. WEIL, S. A. BRANDT, E. L. MILLER, D. D. E. LONG, C. MALTZAHN.*Ceph: A Scalable, High-Performance Distributed File System*, in "7th Symp. Operating Systems Design and Implementation (OSDI '06)", Seattle, WA, Usenix Association, 2006, p. 307-320.