Activity Report Nancy - Grand Est 2017

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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

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Project-Team ALICE

Creation of the Project-Team: 2006 January 09

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1. Personnel

Research Scientists

Bruno Lévy [Team leader, Inria, Senior Researcher, HDR]
Laurent Alonso [Inria, Researcher]
Samuel Hornus [Inria, Researcher]
Sylvain Lefebvre [Inria, Senior Researcher, HDR]
Jonàs Martínez Bayona [Inria, Researcher]
Nicolas Ray [Inria, Researcher]
Erica Schwindt [Inria, Starting Research Position]
Haichuan Song [Inria, Starting Research Position, from Sep 2017]

Faculty Members

Dobrina Boltcheva [Univ de Lorraine, Associate Professor]
Dmitry Sokolov [Univ de Lorraine, Associate Professor, HDR]
Cédric Zanni [Univ de Lorraine, Associate Professor]

External Collaborator

Guillaume Caumon [Univ de Lorraine, from Feb 2017]

Technical Staff

Jose Da Silva Neto [Inria, until Jan 2017]
Jean Hergel [Inria, from Mar 2017 until Jun 2017, granted by ERC (European Research Council Excecutive Agency)]
Yamil Salim Perchy [Inria]
Noemie Vennin [Inria, from Oct 2017]

PhD Students

Jérémie Dumas [Inria, until Jan 2017]
Jimmy Etienne [Inria, from Oct 2017]
Jean Hergel [Inria, until Jan 2017]
Maxence Reberol [Inria]
Julien Renaudeau [Autre entreprise privée]

Post-Doctoral Fellows

Shuo Jin [Inria, until Nov 2017]
Haichuan Song [Inria, until Aug 2017]

Administrative Assistants

Laurence Felicite [Univ de Lorraine, until Jun 2017]
Virginie Priester [CNRS]
Céline Simon [Inria]

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 of 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 [31]. 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 emerged in the mid-1990'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.*, [32]). 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 [22]. 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 [30]. 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, within the context 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 [27]. 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 [24].

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 [28]. We also showed the applicability of this method, by proposing the first algorithm that converts a scanned mesh into a Spline surface automatically [26].

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 [29] or inside volumes [21] [25].

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 within the context of our cooperation with the Gocad consortium, with applications in oil exploration and geomechanics, through co-advised Ph.D. theses (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 [20]. Conversely, some dynamics can be approximated by a series of optimal transport problems, as in the Jordan-Kinderlehrer-Otto scheme [23] 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 sample.

5. Highlights of the Year

5.1. Highlights of the Year

Sylvain Lefebvre initiated the team creation process for MFX (Matter from Graphics), a new team that will focus on synthesizing and designing complex shapes for additive manufacturing.

Jonàs Martínez have been awarded an ANR JCJC 2017 project entitled MuFFin (Microstructures Procedurales et Stochastiques pour la Fabrication Fonctionnelle). MuFFin aims at contributing a unified pipeline for the efficient and scalable synthesis, visualization, and modeling of additively manufactured microstructures with tailored macroscopic physical behavior. In an interdisciplinary effort, MuFFin will blend together computer and material science perspectives to deliver an integrated approach that is both computationally and physically sound.

6. New Software and Platforms

6.1. Graphite

Graphite: The Numerical Geometry Workbench
KEYWORDS: 3D modeling - Numerical Geometry - Texturing - Lighting - CAD - Visualization
SCIENTIFIC DESCRIPTION: Graphite is an experimental 3D modeler, built in 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.
FUNCTIONAL DESCRIPTION: Graphite is a dedicated software platform in numerical geometry that enables, among other things, 3D modelling and texture baking.

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

6.2. GEOGRAM

GEOGRAM : A functions library for geometric programming
KEYWORD: 3D modeling
FUNCTIONAL DESCRIPTION: 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 WARP-DRIVE, the first program that computes semi-discrete optimal transport in 3D.

- Participant: Bruno Lévy
- Contact: Bruno Lévy
- URL: http://alice.loria.fr

6.3. 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 for 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.
FUNCTIONAL DESCRIPTION: Open Numerical Library is a library for solving sparse linear systems, especially designed for the Computer Graphics community. The goal for OpenNL is to be as small as possible, while offering the subset of functionalities required by this application field.

RELEASE FUNCTIONAL DESCRIPTION: * OpenMP parallel solver * more compact data structures, X2 acceleration * SuperLU weak coupling (dynamically loads SuperLU .so if available) (latest version available as part of geogram http://alice.loria.fr/software/geogram/doc/html/index.html)

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

6.4. IceSL

KEYWORD: Additive manufacturing
FUNCTIONAL DESCRIPTION: IceSL allows to model complex shapes through CSG boolean operations. Objects can be directly prepared and sent to a 3d printer for fabrication, without the need to compute an intermediate 3D mesh.

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

6.5. LibSL

Simple Library For Graphics
KEYWORDS: 3D - Graphics
FUNCTIONAL DESCRIPTION: 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

6.6. 3DPrintScaffoldings

KEYWORDS: 3D - 3D modeling - Additive manufacturing
FUNCTIONAL DESCRIPTION: Support generation for additive manufacturing. Optimizes scaffolding made of vertical pillars and horizontal bars that are optimized to use minimal material, be easily removed and support the part at all stages of the fabrication process.

- Participants: Jean Hergel, Jérémie Dumas and Sylvain Lefebvre
- Partner: Université de Lorraine
- Contact: Sylvain Lefebvre
- URL: http://shapeforge.loria.fr/icesl/

6.7. VORPALINE

VORPALINE mesh generator

KEYWORDS: 3D modeling - Unstructured heterogeneous meshes

FUNCTIONAL DESCRIPTION: 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. Geometric foundations

7.1.1. Detecting the Intersection of Two Convex Shapes by Searching on the 2-sphere

Participant: Samuel Hornus.

We take a look at the problem of deciding whether two convex shapes intersect or not. We do so through the well known lens of Minkowski sums and with a bias towards applications in computer graphics and robotics. We describe a new technique that works explicitly on the unit sphere, interpreted as the sphere of directions. In extensive benchmarks against various well-known techniques, ours is found to be slightly more efficient, much more robust and comparatively easy to implement. In particular, our technique is compared favourably to the ubiquitous algorithm of Gilbert, Johnson and Keerthi (GJK), and its decision variant by Gilbert and Foo. We provide an in-depth geometrical understanding of the differences between GJK and our technique and conclude that our technique is probably a good drop-in replacement when one is not interested in the actual distance between two non-intersecting shapes.

The work was published in the journal Computer-Aided Design (special issue for the Proceedings of Solid and Physical Modeling: SPM'17) [9]. The paper has received a best paper award (2nd place) at the SPM conference.

7.1.2. Decomposition of a Hexahedron into a Set of Tetrahedra

Participant: Laurent Alonso.

This year was marked by some works on the combinatorial decomposition of a generic hexahedron in a set of nonintersecting tetrahedra up to symmetries: it is well known that there are only six decompositions of a cube into tetrahedra ; we show that there are at most 1360 potential different decompositions of a hexahedron and at least 1357 are geometrically valid. Additional work is in progress in order to show that the last 3 remaining decompositions do not correspond to valid geometrical solutions.

7.1.3. Hash-based CSG Evaluation on GPU

Participants: Cédric Zanni, Sylvain Lefebvre.

We have developed a new evaluation scheme for Constructive Solid Geometry (CSG) modeling that is well adapted to modern GPU. The approach falls into the category of screen space techniques and can handle a large range of geometric representation. The proposed method relies on the idea of hashing in order to reduce the memory footprint for the processing of a given ray in the scene (e.g. for discovering which part of the space is within or outside the object) while allowing the evaluation of the CSG in amortized constant time. This memory reduction in turn allows to subdivide the space in order to apply progressively the rendering algorithm, ensuring that required data fit in the graphic memory. This improvement over previous approach allows to handle objects of higher complexity during both modeling and slicing for additive manufacturing.

7.2. Geomety processing

7.2.1. Hexahedral Meshes: Generation, Simulation, Evaluation

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

We continued working on the generation of the so-called hexahedral (or hexahedral-dominant) meshes. It is believed that these meshes are more efficient (both in terms of required space and computational time) for certain physics and numerical simulation. However, they are much more difficult to generate, and no fully automatic method currently exists. It is a huge problem in the industry, that uses days/weeks/months of manual work to generate them, because they are preferred in certain domains (fluids, mechanics, wave propagation). In this research, we aim at answering the following questions:

- How can we generate a hexahedral (or hex-dominant) mesh in a fully automatic manner?
- How can we evaluate the quality of this mesh, suitability for numerical simulation?

In the context of Maxence Reberol's Ph.D. thesis, we developed new algorithms to answer both questions. To answer the first question, in [17], building on our previous results based on global parameterization, we proposed a method to mesh the globality of the domain, by isolating the singular zones of the parameterization and meshing them with a separate algorithm. To answer the second question, in [16], we proposed a new method to estimate the distance between two Finite Element simulations obtained from two different computational meshes / function bases. We started using our algorithm to compare the rate of convergence of the method as a function of element size h with different PDEs (Poisson, linear elasticity) using different function bases (tetrahedral: P1, P2, P3, hexahedral: Q1, Q2, Q3).

7.2.2. Surface Reconstruction

Participants: Dobrina Boltcheva, Bruno Lévy.

We developed a new algorithm [7] for surface reconstruction. Our algorithm is equivalent to Delaunay-based reconstruction, it computes the Delaunay triangulation restricted to an object computed from the input pointset. The object is a set of disks centered on the input points and perpendicular to estimated normals. The algorithm is fast and memory efficient, because the only used global data structure is a Kd-tree. Applications are demonstrated with a parallel implementation on a multicore processor, and a version for hand-held devices.

7.2.3. Geometric Algorithms for 3D modeling in Geo-sciences

Participants: Bruno Lévy.

We developed RingMesh [13], an application layer around our Geogram library, specialized for 3D modeling in Geo-sciences. The RingMesh library uses the mesh data structure and basic algorithms in Geogram to offer 3D modeling primitives well-suited to geosciences. It has datatypes to efficiently represent complicated 3D models of the underground, with the topological relationships between the interfaces (horizons and faults), as well as interfaces to 3D mesh generation softwares.

7.3. Additive Manufacturing

7.3.1. Iterative Carving for Self-supporting 3D Printed Cavities

Participants: Samuel Hornus and Sylvain Lefebvre.

This work explores the printing of shapes with as little material as possible, mostly with a view toward minimizing fabrication time for large pieces. In particular, it aims at modeling a structure of thin sheets inside a volume in such a way that the sheets and the boundary of the volume can be 3D-printed as is, without internal support.

The work is an adaptation of the technique developed earlier fo other applications in 3D printing and achieved state-of-the-art results. It is available as an Inria technical report [14].

7.3.2. Optimal Discrete Slicing

Participant: Sylvain Lefebvre.

This work is a collaboration with Marc Alexa and Kristian Hildebrand from TU Berlin. We developed a novel algorithm to compute the optimal decomposition of a 3D shape into layers of varying thickness, in a discrete setting. This answers a long standing problem in additive manufacturing. Our approach computes all optimal solutions for any number of slices by formulating the optimization as a dynamic programming problem. We developed efficient algorithms for both computing the geometric errors within each slice (based on volume difference) as well as for the optimizer. Our technique is the first to provide a provably optimal result and outperforms all existing heuristics. The work has been published in ACM TOG [5], presented at SIGGRAPH 2017 and is fully implemented within IceSL, available for public download.

7.3.3. Fabricable Tile Decors

Participants: Sylvain Lefebvre and Jonàs Martínez.

We propose a modeling technique to produce large objects whose surface is composed of user-provided decorative tiles. Such objects are very inefficient to 3D print as they occupy a large volume while in fact using little material. On low end printers they require large amounts of support structures which are difficult to remove. We propose a decomposition of the input shape into sets of planar patches that can print flat and can be later assembled into stable structures. This work is a collaboration with Hong Kong University in the context of the PrePrint3D associated team. It was published in ACM TOG [8] and presented at SIGGRAPH Asia 2017.

7.3.4. Visualizing and Fabricating Complex Internal Structures

Participant: Sylvain Lefebvre.

This work considers efficient display and manufacturing of extremely detailed internal structures described by implicit (procedural) indicator functions [15]. We describe a technique for their progressive rendering when the structures fill an envelope provided as a 3D mesh. We also describe how to efficiently extract slices for additive manufacturing, in a process that is both computationally and memory efficient. This work was presented at the Visual Analytics conference (Moscow, 2017) and is under submission to the Scientific Visualization journal.

7.3.5. Orthotropic k-nearest Foams for Additive Manufacturing

Participants: Jonàs Martínez, Haichuan Song, Jérémie Dumas, Sylvain Lefebvre.

We proposed a novel metamaterial with controllable, freely orientable, orthotropic elastic behavior – orthotropy means that elasticity is controlled independently along three orthogonal axes, which leads to materials that better adapt to uneven, directional load scenarios, and offer a more versatile material design primitive. The fine-scale structures are generated procedurally by a stochastic process, and resemble a foam. This work has been published in ACM TOG [12], and presented at SIGGRAPH 2017.

7.3.6. Color Fused Filament Fabrication

Participants: Haichuan Song, Sylvain Lefebvre.

Traditional filament printers cannot truly reproduce colored objects. The best current techniques rely on a form of dithering exploiting occlusion, that was only demonstrated for shades of two base colors and that behaves differently depending on surface slope. We explored a novel approach for 3D printing colored objects, capable of creating controlled gradients of varying sharpness. Our technique exploits off-the-shelves nozzles that are designed to mix multiple filaments in a small melting chamber, obtaining intermediate colors once the mix is stabilized. The key idea is to divide each input layer into a set of sublayers, each having a different constant color. By locally changing the thickness of the sublayers, we change the color that is perceived at a given location. By optimizing the choice of colors of each sublayer, we further improve quality and allow the use of different numbers of input filaments. We demonstrate our results by building a functional color printer using low cost, off-the-shelves components. Using our tool a user can paint a 3D model and directly produce its physical counterpart, using any material and color available for fused filament fabrication. This work has been submitted and is available at [18].

7.3.7. Anti-aliasing for Fused Filament Deposition

Participants: Haichuan Song, Sylvain Lefebvre.

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 also largely increases the print time. We proposed a simple yet effective technique to improve the print accuracy for layered manufacturing by filament deposition. It better reproduces the geometry of sloped surfaces without increasing the print time. The 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 further split and order paths to minimize defects due to the extruder nozzle shape, avoiding any change to 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. This work has been published in the Computer Aided Design (CAD) journal [19].

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

We developed a collaboration with a local company regarding additive manufacturing technologies. This contract allowed us to host two interns (Mélanie Siret and Jimmy Etienne), both supervised by Sylvain Lefebvre. The topic is confidential.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. 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.

9.1.2. 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 filaments 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.

9.2. National Initiatives

9.2.1. EXPLORAGRAM

Inria exploratory project EXPLORAGRAM (in cooperation with MOKAPLAN): We explored new algorithms for computational optimal transport. The project allowed us to hire a post-doc for 18 months (Erica Schwindt). She worked on the semi-discrete algorithm, and its application to the simulation of fluid-structure interactions. The project allowed to strengthen the cooperation with MOKAPLAN. It also allowed us to start exploring new cooperations, with Institut d'Astrophysique de Paris, on early universe reconstruction.

9.2.2. ANR MAGA (2016-2020)

We participate to the ANR MAGA (ANR-16-CE40-0014) on the Monge Ampere equation and computational geometry. In this ANR project, we cooperate with Quentin Merigot and other researchers of the MOKAPLAN Inria team on new computational methods for optimal transport.

9.2.3. ANR ROOT (2016-2020)

We participate to the Young Researcher ANR ROOT (ANR-16-CE23-0009) on Optimal Transport for computer graphics, with Nicolas Bonneel (CNRS Lyon) as Principal Investigator. In the context of this project, we develop a new symmetric algorithm for semi-discrete optimal transport that optimizes for both the location of the samples and their Lagrange multipliers. An ENS training period will start in Jan. 2018 (Agathe Herrou), hosted in Nancy.

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

9.3.1.1. SHAPEFORGE

Title: ShapeForge: By-Example Synthesis for Fabrication

Program: FP7 (ERC Starting Grant)

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.

9.3.1.2. ICEXL

Title: IceXL: Advanced modeling and slicing software for additive manufacturing

Program: FP7 (ERC Proof of Concept)

Duration: November 2016 - February 2018

Coordinator: Inria

Inria contact: Sylvain Lefebvre

The ICEXL Proof of Concept projects aims at further developing our software IceSL and its industrial potential. We have released several new major features than allowed the software to gain visibility (as shown by a strong increase in downloads towards the end of 2017, 1500+ downloads in November). We have teamed with a selected number of industrial partners to work towards industrial use, and have ongoing discussions regarding technology transfer and licensing.

9.4. International Initiatives

9.4.1. Inria Associate Teams Not Involved in an Inria International Lab

9.4.1.1. PREPRINT3D

Title: Model Preparation for 3D Printing

International Partner (Institution - Laboratory - Researcher):

HKU (Hong Kong, China) - Department of Computer Science (CS) - Wenping Wang

Start year: 2017

We seek to develop novel ways to prepare and model 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.

9.4.2. Inria International Partners

9.4.2.1. Informal International Partners

Jean-Francois Remacle (University of Louvain, Belgium), we cooperate on hexahedral-dominant meshing (visits, students exchange). Our former Ph.D. student Jeanne Pellerin is doing a post-doc in his lab.

9.5. International Research Visitors

9.5.1. Visits of International Scientists

Li-Yi Wei visited us from 05/04/17 to 18/04/17 to work on the topic of element based topology optimization with Jérémie Dumas, Jonàs Martínez and Sylvain Lefebvre. This work was submitted to SIGGRAPH but not accepted, we plan to resubmit it early 2018.

9.5.1.1. Internships

Sylvain Lefebvre supervised Mélanie Siret for a 3 months internship, as well as Jimmy Etienne for a 6 months internship.

9.5.2. Visits to International Teams

B. Lévy and Nicolas Ray visited Jean-Francois Remacle (U. Louvain, Belgium). B. Lévy visited Jan Obloj (Oxford, U.K.).

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

We organized a free workshop on February 2017 (http://shapeforge.loria.fr/workshop/) in-between the PhD defenses of Jean Hergel and Jérémie Dumas. International jury members gave talks; the workshop was open to the public. We recorded all the talks and made them available online (https://www.youtube.com/playlist?list=PLfUzw-QfoyuWLPJpCCp6xwTAPMIjt7Q-k).

10.1.1.2. Member of the Organizing Committees

B. Lévy is an elected member of the steering committee of Shape Modeling Association (since 2017).

10.1.2. Scientific Events Selection

10.1.2.1. Chair of Conference Program Committees

Sylvain Lefebvre was program co-chair for SMI 2017. B. Lévy was conference co-chair of WSOM 2017.

10.1.2.2. Member of the Conference Program Committees

B. Lévy was program committee member of Eurographics 2017, SGP 2017, SPM 2017

10.1.2.3. Reviewer

Members of the team were reviewers for SoCG'17, Eurographics, SIGGRAPH, Computer Aided Design, Pacific Graphics, and SPM.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- B. Lévy is a member of the editorial board of ACM Transactions on Graphics.
- B. Lévy is a member of the editorial board of Graphical Models (Elsevier)
- B. Lévy is a member of the editorial board of Computer Graphics and Applications
- Sylvain Lefebvre was associated editor for ACM Transactions on Graphics.

10.1.3.2. Reviewer - Reviewing Activities

Members of the team were reviewers for Computer Aided Design (CAD),Discrete Applied Mathematics (Elsevier), Transactions on Visualization and Computer Graphics (IEEE), and Computers & Graphics (Elsevier).

10.1.4. Invited Talks

B. Lévy gave an invited keynote talk at Eurographics 2017

10.1.5. Research Administration

Samuel Hornus was a moderator of the CDT (Technological Development Commission) of CRI Nancy.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Licence: Samuel Hornus, Module « mathématiques appliquées à l'informatique » (MAI). 64h eq. TD, niveau L3. à Télécom Nancy, France.

Licence: Cédric Zanni, Informatique 2, 40h ETD, L3, École des Mines de Nancy, France.

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

Master: Nicolas Ray, Initiation à la recherche, 10 heures, M1, 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: Cédric Zanni, Database essentials, 24h ETD, M1, École des Mines de Nancy, France.

Master: Cédric Zanni, Techniques de l'animation et du jeu vidéo, 27h ETD, M1, École des Mines de Nancy, France.

Master: Cédric Zanni, Software Engineering, 18h ETD, M1, École des Mines de Nancy, France.

Master: Cédric Zanni, Operating System, 17h ETD, M1, École des Mines de Nancy, France.

Master: Cédric Zanni, Introduction au C/C++, 34h ETD, M1, École des Mines de Nancy, France.

Master: Cédric Zanni, UML, 4h ETD, M1, École des Mines de Nancy, France.

Master: B. Lévy teaches Numerical Methods in École nationale supérieure de géologie de Nancy, France (12h).

Master: B. Lévy teaches Algorithmic Gems in École des Mines de Nancy, France (8h).

10.2.2. Supervision

Ph.Ds in progress supervised by B. Lévy:

- Maxence Reberol, Finite elements on hex-dominant meshes, third year. Funding: ERC ShapeForge and région Lorraine. Defense: February 15th 2018.
- Pierre Anquez, Robust meshing of geological data, consortium GOCAD, second year, co-supervised with Guillaume Caumon.
- Julien Renaudeau, Constrained geo-modelling using implicit functions, second year, Cifre Schlumberger, co-supervised with Guillaume Caumon.

Jérémie Dumas and Jean Hergel, supervised by Sylvain Lefebvre, defended their PhD theses in February 2017. Jérémie Dumas received the University of Lorraine award for the best 2017 PhD thesis in Computer Science.

10.2.3. Juries

Sylvain Lefebvre was "rapporteur" for the PhD of Benoit Arbelot (Grenoble Universities, defended April 7 2017), for the PhD thesis of Luigi Malomo (CNR Pisa) and Christian Santoni (Computational Design Lab, University of Rome).

10.3. Popularization

Haichuan Song, Sylvain Lefebvre and Salim Perchy presented IceSL at a booth at the Maker Faire Rome 2017 (http://www.makerfairerome.eu/en/). This is a major event with 100K+ visitors every year. We presented the software to students, general public and 3D printing enthusiasts. We received a Maker of Merit award for our project.

Sylvain Lefebvre participated to the radio program "La méthode scientifique" on France Culture, aired on November 8 2017 (https://www.franceculture.fr/emissions/la-methode-scientifique/la-methode-scientifique-mercredi-8-novembre-2017).

B. Lévy gave an invited talk at "Forum Art Inovation" organized by IRCAM, Paris, Pompidou center (16-03-2017): http://medias.ircam.fr/stream/ext/video/files/2017/04/04/Vertigo_16mars2017_%20BrunoLevy_GB.mov.webm.

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Major publications by the team in recent years

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[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.

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Publications of the year

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[6] S. ARANOVSKIY, R. ORTEGA, J. G. ROMERO, D. SOKOLOV.*A Globally Exponentially Stable Speed Observer for a Class of Mechanical Systems: Experimental and Simulation Comparison with High-Gain and Sliding Mode Designs*, in "International Journal of Control", November 2017, p. 1 - 14 [*DOI :* 10.1080/00207179.2017.1404130], https://hal.inria.fr/hal-01658753.

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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

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Project-Team BIGS

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

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A3.2. - Knowledge
A3.2.3. - Inference
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A3.3.1. - On-line analytical processing
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B2.2.3. - Cancer
B2.3. - Epidemiology
B2.4. - Therapies
B5.5. - Materials

1. Personnel

Research Scientists

Romain Azais [Inria, Researcher]
Bruno Scherrer [Inria, Researcher, HDR]

Faculty Members

Anne Gégout Petit [Team leader, Univ de Lorraine, Professor, HDR]
Thierry Bastogne [Univ de Lorraine, Associate Professor, HDR]
Sandie Ferrigno [Univ de Lorraine, Associate Professor]
Sophie Mezieres [Univ de Lorraine, Associate Professor]
Jean Marie Monnez [Univ de Lorraine, Professor, HDR]
Aurelie Muller-Gueudin [Univ de Lorraine, Associate Professor]
Samy Tindel [Univ de Lorraine, Professor, HDR]
Pierre Vallois [Univ de Lorraine, Professor, HDR]

External Collaborator

Celine Lacaux [Univ d'Avignon et des pays du Vaucluse, HDR]

PhD Students

Lévy Batista [Univ de Lorraine, until Oct 2017]
Kévin Duarte [Centre hospitalier universitaire de Nancy]
Florine Greciet [Autre entreprise privée]
Pauline Guyot [Univ de Lorraine]
Clemence Karmann [Inria]
Nassim Sahki [Inria, from Nov 2017]

Post-Doctoral Fellow

Florian Bouguet [Inria, until Aug 2017]

Administrative Assistant

Celine Simon [Inria]

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-UL laboratory in mathematics, of which Inria is a strong partner. One member of BIGS, T. Bastogne, comes from the Centre de Recherche en Automatique de Nancy (CRAN), laboratory in the domain of Automatics with which BIGS has strong relations in the domain "Health-Biology-Signal". 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.

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 [79], [56]. Piecewise deterministic processes are non diffusion processes also frequently used in the biological context [45], [55], [47]. Among Markov model, we also developed strong expertise about processes derived from Brownian motion and Stochastic Differential Equations [71], [54]. For instance, knowledge about Brownian or random walk excursions [78], [70] 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 of fractional fields. The basic aspects of these differential equations are now well understood, mainly thanks to the so-called *rough paths* tools [62], but also invoking the Russo-Vallois integration techniques [72]. The specific issue of Volterra equations driven by fractional Brownian motion, which is central for the subdiffusion within proteins problem, is addressed in [46]. Many generalizations (Gaussian or not) of this model have been recently proposed for some Gaussian locally self-similar fields, or for some non-Gaussian models [59], or for anisotropic models [42].

3.3. Estimation and control for stochastic processes

We develop inference about stochastic processes that we use for modeling. Control of stochastic processes is also a way to optimise administration (dose, frequency) of therapy.

There are many estimation techniques for diffusion processes or coefficients of fractional or multifractional Brownian motion according to a set of observations [58], [37], [44]. But, the inference problem for diffusions driven by a fractional Brownian motion has been in its infancy. Our team has a good expertise about inference of the jump rate and the kernel of Piecewise Deterministic Markov Processes (PDMP) [34], [35], [33], [36]. 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 tackle the problem of inference of "Hidden PDMP". About pharmacokinetics modeling inference, we want to take into account for presence of timing noise and identification from longitudinal data. We have expertise on this subjects [38], and we also used mixed models to estimate tumor growth [39].

We consider the control of stochastic processes within the framework of Markov Decision Processes [69] and their generalization known as multi-player stochastic games, 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 [41]. Regarding complexity, a central topic of research is the analysis of the Policy Iteration algorithm, which has made significant progress in the last years [81], [68], [53], [77], 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 [75], [74], [76], [61], [73], 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 pairs of these nodes called edges. This type of data is frequently used in biology because they provide a mathematical representation of many concepts such as biological structures and networks of relationships in a population. Some attention has recently been focused in the group on modeling and inference for graph data.

Network inference is the process of making inference about the link between two variables taking into account the information about other variables. [80] gives a very good introduction and many references about network inference and mining. Many methods are available to infer and test edges in Gaussian Graphical models [80], [63], [50], [51]. However, when dealing with abundance data, because inflated zero data, we are far from gaussian assumption and we want to develop inference in this case.

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. We also work on lossy compression of trees via linear directed acyclic graphs. These methods enable us to compute distances between tree data faster than from the original structures and with a high accuracy.

3.5. Regression and machine learning

Regression models or machine learning aim at inferring statistical links between a variable of interest and covariates. In biological study, it is always important to develop adapted learning methods both in the context of *standard* data and also for data of high dimension (with sometimes few observations) and very massive or online data.

Many methods are available to estimate conditional quantiles and test dependencies [67], [57]. Among them we have developed nonparametric estimation by local analysis via kernel methods [48], [49] and we want to study properties of this estimator in order to derive a 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 develop omnibus test that examine several assumptions together.

Concerning the analysis of high dimensional data, our view on the topic relies on the *French data analysis school*, specifically on Factorial Analysis tools. In this context, stochastic approximation is an essential tool [60], which allows one to approximate eigenvectors in a stepwise manner [66], [64], [65]. BIGS aims at performing accurate classification or clustering by taking advantage of the possibility of updating the information "online" using stochastic approximation algorithms [43]. We focus on several incremental procedures for regression and data analysis like linear and logistic regressions and PCA.

We also focus on the biological context of high-throughput bioassays in which several hundreds or thousands of biological signals are measured for a posterior analysis. We have to account for the inter-individual variability within the modeling procedure. 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-oncology

On this subject, we have new collaborations with clinicians and we want to propose branching processes to model appearance of mutations in tumor. The observed process is the "circulating DNA" (ctDNA). The final purpose is to use ctDNA as a early biomarker of the resistance to an immunotherapy treatment. It is the subject of gthe ITMO project. Another subject is the identification of dynamic network of expression We continue our work on low-grade gliomas. The ongoing collaboration with Montpellier CHU, and a new one with Montreal CRHUM should provide us more data. We initiate as well interactions with researchers from Montreal LIO to extend the previous work. We still have much work to do in modeling to reach our goal of a decision-aid tool for personalised medicine. In the same context, there is a question of clustering analysis of a brain cartography obtained by sensorial simulations during awake surgery.

4.2. Genomic data and micro-organisms population study

Despite of his 'G' in the name of BIGS, Genetics is not central in the applications of the team. However, we want to contribute to a better understanding of the correlations between genes trough their expression data and of the genetic bases of drug response and disease. We have contributed to methods detecting proteomics and transcriptomics variables linked with the outcome of a treatme

4.3. Epidemiology and e-health

We have many works to do in our ongoing projects in the context of personalized medicine with "CHU Nancy". They deal with biomarkers research; prognostic value of quantitative variables and events and scoring, of adverse events. We also want to develop our expertise in rupture detection in a project with APHP for the detection of adverse events, earlier than the clinical signs and symptoms. The clinical relevance of predictive analytics is obvious for high-risk patients such as those with solid organ transplantation or severe chronic respiratory disease for instance. The main challenge is the rupture detection in multivariate and heterogeneous signals (for instance daily measures of electrocardiogram (during 30mn), body temperature, spirometry parameters, sleep duration, etc ... Other collaborations with clinicians concern foetopathology and we want to use our work on conditional distribution function to explain fetal and child growth. We have data from the "Service de foetopathologie et de placentologie" of the "Maternité Régionale Universitaire" (CHU Nancy).

4.4. Dynamics of telomeres

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. Trough a beginning collaboration with Pr A. Benetos, geriatrician at CHU Nancy, we recently data on the distribution of the length of telomeres from blood cells. With some members of Inria team TOSCA, we want to work in three connected directions: (1) refine methodology for the analysis of the available data; (2) propose a dynamical model for the lengths of telomeres and study its mathematical properties (long term behavior, quasi-stationarity, etc); and (3) use these properties to develop new statistical methods. A slot of postdoc position is already planned in the Lorraine Université d'Excellence, LUE project GEENAGE (managed by CHU Nancy).

5. New Software and Platforms

5.1. Angio-Analytics

KEYWORDS: Health - Cancer - Biomedical imaging
SCIENTIFIC DESCRIPTION: This tool allows the pharmacodynamic characterization of anti-vascular effects in anti-cancer treatments. It uses time series of in vivo images provided by intra-vital microscopy. Such in vivo images are obtained owing to skinfold chambers placed on mice skin. The automatized analysis is split up into two steps that were completely performed separately and manually before. The first steps corresponds to image processing to identify characteristics of the vascular network. The last step is the system identification of the pharmacodynamic response and the statistical analysis of the model parameters.
FUNCTIONAL DESCRIPTION: Angio-Analytics allows the pharmacodynamic characterization of anti-vascular effects in anti-cancer treatments.

- Participant: Thierry Bastogne
- Contact: Thierry Bastogne

5.2. In silico

In silico design of nanoparticles for the treatment of cancers by enhanced radiotherapy
KEYWORDS: Bioinformatics - Cancer - Drug development

FUNCTIONAL DESCRIPTION: To speed up the preclinical development of medical engineered nanomaterials, we have designed an integrated computing platform dedicated to the virtual screening of nanostructured materials activated by X-ray making it possible to select nano-objects presenting interesting medical properties faster. The main advantage of this in silico design approach is to virtually screen a lot of possible formulations and to rapidly select the most promising ones. The platform can currently handle the accelerated design of radiation therapy enhancing nanoparticles and medical imaging nano-sized contrast agents as well as the comparison between nano-objects and the optimization of existing materials.

- Participant: Thierry Bastogne
- Contact: Thierry Bastogne

5.3. SesIndexCreatoR

FUNCTIONAL DESCRIPTION: This package allows computing and visualizing socioeconomic indices and categories distributions from datasets of socioeconomic variables (These tools were developed as part of the EquitArea Project, a public health program).

- Participants: Benoît Lalloué, Jean-Marie Monnez, Nolwenn Le Meur and Severine Deguen
- Contact: Benoît Lalloué
- URL: http://www.equitarea.org/documents/packages_1.0-0/

6. New Results

6.1. Stochastic modelling

Participants: T. Bastogne, P. Vallois, S. Wantz-Mezieres, L. Batista, A. Gégout-Petit

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 [39], [40]. We recently improved this methodology for the analysis of data collected in vivo for growth tumor for the biopharmaceutical company Transgene. The problem was to measure the differential effect of treatments (different molecules and doses) on the dynamics of the tumor taking into account the effect of censoring [10].

In the framework of the esca-illness of vines, we 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 tests based on the join count statistics [6].

6.2. Estimation and control for Markov Processes

Participants: R. Azais, F. Bouguet, T. Bastogne

We have developed statistical inference techniques for estimating the jump rate of PDMPs (piecewise-deterministic Markov processes) [2] which is an essential step to build relevant application models. In [2], we state a new characterization of the jump rate when the transition kernel only charges a discrete subset of the state space and deduce from it a competitive nonparametric technique for estimating this feature of interest. Our methodologies have been illustrated on numerical examples and real data. We also investigated the probabilistic properties of the PDMPs [5] or more general Markov processes [31] that could be useful to study properties of estimators.

A bit more generally, we have made contributions to a variety of specific estimation problems. We considered the problem of estimation of integrals under Markov design, which has a large variety of applications, in particular in biology and climatology. In [24], we have developed and analyzed a technique for estimating the average value over space when sensors describe a Markovian trajectory; this method leads to rates that are better than the traditional "root n"-rate, where n is the sample size, and was applied to the evaluation of the average temperature of oceans.

Control of stochastic processes is also a way to optimise administration (dose, frequency) of therapy. In [8], we have presented the design and validation of a real time controller able to track a preset photobleaching trajectory by modulating the width of light impulses during the treatment sessions, which is useful in a Photodynamic therapy context. This innovative solution was validated by *in vivo* experiments that have shown a significantly improvement of reproducibility of the inter-individual photobleaching kinetics. This innovative controller is the first personalized solution able to adapt in realtime the dose of light to be applied in photodynamic therapy.

6.3. Algorithms and Estimation for graph data

Participants: R. Azais, F. Bouguet, T. Bastogne

Tree-structured data naturally appear in various fields, particularly in biology where plants and blood vessels may be described by trees. The paper [27] 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.

6.4. Regression and machine learning

Participants: A. Gégout-Petit, A. Muller-Gueudin, T. Bastogne, L. Batista, R. Azais, S. Ferrigno, K. Duarte, J.-M. Monnez

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 [32].

We study 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 [25]. 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).

In the purpose of selecting 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 lung cancer [21], [19], [20].

We also focus on the biological context of high-throughput and high-content bioassays in which several hundreds or thousands of biological signals are measured for a posterior analysis. In this experimental context, each culture well is a biological system in which the output variable is the cell proliferation, the input variable can be an electrical or a light stimulus signal and the covariate may be the type of cells, type of medium or tested compounds. The ambition is to identify a batch of several thousands of wells in a single step with the same model structure. Mixed effects models are largely used in regression but up to now they have rarely been used in the field of dynamical system identification. Our approach aims 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 parameter [13], [10].

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

7.1.1. Bilateral Contracts with Industry

7.1.1.1. 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.

7.1.1.2. 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.

7.1.1.3. 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 [52].

7.1.1.4. CYBERNANO (2014-2017)

Participants: T. Bastogne, L. Batista, P. Guyot
Cybernano is a start-up founded in 2013 by one BIGS member: T. Bastogne. Cybernano develops computational services to analyze high-content data in cell biology for applications in oncology, cardiotoxicity and virology. After the end of his PhD (2017), L. Batista became chief technical officer of Cybernano. A EuroStars project proposal was submitted in Sep. 2017 in which Cybernano will be the leader and BIGS a scientific partner (Eurostars is a H2020 programme that supports research-performing small and medium enterprises).

8. Partnerships and Cooperations

8.1. National Initiatives

- *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.
- 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
- "ITMO Physics, mathematics applied to Cancer" (2017-2019): "Modeling ctDNA dynamics for detecting targeted therapy", Funding organisms: ITMO Cancer, ITMO Technologies pour la santé de l'alliance nationale pour les sciences de la vie et de la santé (AVIESAN), INCa, Leader: N. Champagnat (Inria TOSCA), Participants: A. Gégout-Petit, A. Muller-Gueudin, P. Vallois
- Modular, multivalent and multiplexed tools for dual molecular imaging (2017-2020), Funding organism: ANR, Leader: B Kuhnast (CEA). Participant: T. Bastogne.

8.2. European Initiatives

8.2.1. 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.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

- BIGS team has organized a two-days workshop “Statistique pour les processus de Markov déterministes par morceaux” in Nancy, with about 40 participants, among which most members of the team. See http://pdmp2017.iecl.univ-lorraine.fr/

9.1.2. Scientific Events Selection

9.1.2.1. 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.

9.1.3. Journal

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

9.1.3.1. 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...

9.1.4. 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)

9.1.5. Scientific Expertise

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

9.1.6. 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.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

R. Azaïs and B. Scherrer excepted, BIGS members have teaching obligations at "Université de Lorraine" and are teaching at least 192 hours each year. They teach probability and statistics at different level (Licence, Master, Engineering school). Many of them have pedagogical responsibilities.

9.2.2. 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.
- 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: 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

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Team CAMUS

Compilation pour les Architectures MUlti-coeurS

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:

A1.1.1. - Multicore, Manycore
A1.1.4. - High performance computing
A2.1.1. - Semantics of programming languages
A2.1.6. - Concurrent programming
A2.2.1. - Static analysis
A2.2.3. - Run-time systems
A2.2.4. - Parallel architectures
A2.2.5. - GPGPU, FPGA, etc.
A2.2.6. - Adaptive compilation

Other Research Topics and Application Domains:

B4.5.1. - Green computing
B6.1.1. - Software engineering
B6.6. - Embedded systems

1. Personnel

Research Scientists

Arthur Charguéraud [Inria, Researcher]
Jens Gustedt [Inria, Senior Researcher, HDR]

Faculty Members

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

Technical Staff

Maxime Mogé [Inria]

PhD Students

Yann Barsamian [Univ de Strasbourg]
Paul Godard [Caldera]
Salwa Kobeissi [Inria, from Sep 2017]
Harenome Ranaivoarivony-Razanajato [Univ de Strasbourg]
Mariem Saied [Univ de Strasbourg, until Aug 2017]
Daniel Salas [INSERM]
Maxime Schmitt [Univ de Strasbourg]

Post-Doctoral Fellows

Manuel Selva [Inria]
Julien Pagès [Univ. Strasbourg, from Sept 2016, until Aug 2017]

Administrative Assistants

Véronique Constant [Inria]

Ouiza Herbi [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 [32]. 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.

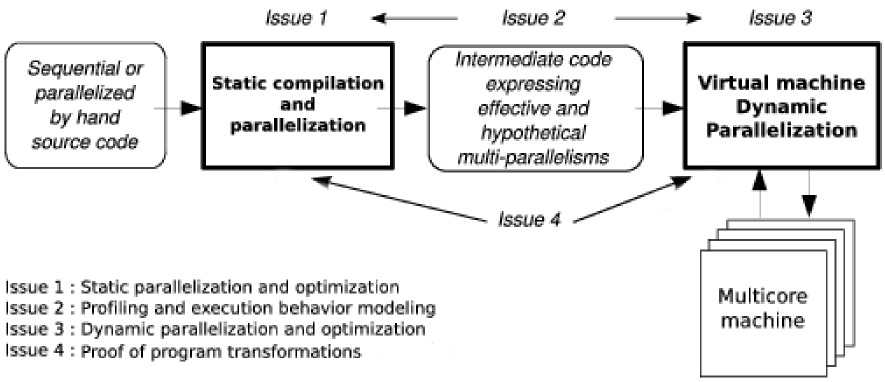

Figure 1. Automatic parallelizing steps for multicore architectures

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 [30]. 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 [33]. 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 primary 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

5.1.1. Awards

A team composed of four CAMUS members (Cédric Bastoul, Vincent Loechner, Harenome Ranaivoarivony-Razanajato and Maxime Schmitt) participated to the Google Hash Code contest. They were ranked 9 during the qualification round, over more than 26000 participants from Europe, Middle-East and Africa, and qualified for the final. They were 34th at the final hosted in the Google Paris office.

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: Aravind Sukumaran-Rajam, Juan Manuel Martinez Caamaño, Manuel Selva and Philippe Clauss
- Contact: Philippe Clauss
- URL: http://apollo.gforge.inria.fr

6.2. Clan

A Polyhedral Representation Extraction Tool for C-Based High Level Languages
KEYWORD: Polyhedral compilation
FUNCTIONAL DESCRIPTION: Clan is a free software and library which translates some particular parts of high level programs written in 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++ or Java). Clan is notably the frontend of the two major high-level compilers Pluto and PoCC.

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

6.3. 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/

6.4. 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.

RELEASE FUNCTIONAL DESCRIPTION: It mostly solves building and offers a better OpenScop support.

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

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.

RELEASE FUNCTIONAL DESCRIPTION: The IBB compiler has been improved in some aspects in 2014: loop bounds can now be min and max functions, IBB uses the OpenScop format to encode statements and iteration domains.

- Participants: Cédric Bastoul, Imèn Fassi and Philippe Clauss
- 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
KEYWORDS: Rational polyhedra - Library - Polyhedral compilation
SCIENTIFIC DESCRIPTION: A C library used in polyhedral compilation, as a basic tool used to analyze, transform, optimize polyhedral loop nests. Has been shipped in the polyhedral tools Cloog and Pluto.
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

Ordered Read-Write Lock
KEYWORDS: Task scheduling - Deadlock detection
FUNCTIONAL DESCRIPTION: ORWL is a reference implementation of the Ordered Read-Write Lock tools. The macro definitions and tools for programming in C99 that have been implemented for ORWL have been separated out into a toolbox called P99.

- Participants: Jens Gustedt, Mariem Saied and Stéphane Vialle
- Contact: Jens Gustedt
- Publications: Iterative Computations with Ordered Read-Write Locks - Automatic, Abstracted and Portable Topology-Aware Thread Placement - Resource-Centered Distributed Processing of Large Histopathology Images - Automatic Code Generation for Iterative Multi-dimensional Stencil Computations

6.9. P99

KEYWORD: Macro programming
FUNCTIONAL DESCRIPTION: P99 is a suite of macro and function definitions that ease the programming in modern C, minimum C99. By using tools from C99 and C11 we implement default arguments for functions, scope bound resource management, transparent allocation and initialization.

- Participants: Jens Gustedt, Mariem Saied and Stéphane Vialle
- Contact: Jens Gustedt
- URL: https://gforge.inria.fr/projects/p99/

6.10. stdatomic

standard atomic library
KEYWORD: Atomic access
SCIENTIFIC DESCRIPTION: We present a new algorithm and implementation of a lock primitive that is based on Linux' native lock interface, the futex system call. It allows us to assemble compiler support for atomic data structures that can not be handled through specific hardware instructions. Such a tool is needed for C11's atomics interface because here an _Atomic qualification can be attached to almost any data type. Our lock data structure for that purpose meets very specific criteria concerning its field of operation and its performance. By that we are able to outperform gcc's libatomic library by around 60%.

FUNCTIONAL DESCRIPTION: This implementation builds entirely on the two gcc ABIs for atomics. It doesn't even attempt to go down to assembly level by itself. We provide all function interfaces that the two gcc ABIs and the C standard need. For compilers that don't offer the direct language support for atomics this provides a syntactically reduced but fully functional approach to atomic operations.

- Author: Jens Gustedt
- Contact: Jens Gustedt
- Publications: Futex based locks for C11's generic atomics - Futex based locks for C11's generic atomics (extended abstract)
- URL: http://stdatomic.gforge.inria.fr/

6.11. musl

KEYWORDS: Standards - Library
SCIENTIFIC DESCRIPTION: musl provides consistent quality and implementation behavior from tiny embedded systems to full-fledged servers. Minimal machine-specific code means less chance of breakage on minority architectures and better success with "write once run everywhere" C development.

musl's efficiency is unparalleled in Linux libc implementations. Designed from the ground up for static linking, musl carefully avoids pulling in large amounts of code or data that the application will not use. Dynamic linking is also efficient, by integrating the entire standard library implementation, including threads, math, and even the dynamic linker itself into a single shared object, most of the startup time and memory overhead of dynamic linking have been eliminated.
FUNCTIONAL DESCRIPTION: We participate in the development of musl, 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
- URL: http://www.musl-libc.org/

6.12. Modular C

KEYWORDS: Programming language - Modularity
FUNCTIONAL DESCRIPTION: The change to the C language is minimal since we only add one feature, composed identifiers, to the core language. Our modules can import other modules as long as the import relation remains acyclic and a module can refer to its own identifiers and those of the imported modules through freely chosen abbreviations. Other than traditional C include, our import directive ensures complete encapsulation between modules. The abbreviation scheme allows to seamlessly replace an imported module by another one with equivalent interface. In addition to the export of symbols, we provide parameterized code injection through the import of "snippets". This implements a mechanism that allows for code reuse, similar to X macros or templates. Additional features of our proposal are a simple dynamic module initialization scheme, a structured approach to the C library and a migration path for existing software projects.

- Author: Jens Gustedt
- Contact: Jens Gustedt
- Publications: Modular C - Arbogast: Higher order AD for special functions with Modular C - Futex based locks for C11's generic atomics
- URL: http://cmod.gforge.inria.fr/

6.13. arbogast

KEYWORD: Automatic differentiation

SCIENTIFIC DESCRIPTION: This high-level toolbox for the calculus with Taylor polynomials is named after L.F.A. Arbogast (1759-1803), a French mathematician from Strasbourg (Alsace), for his pioneering work in derivation calculus. Its modular structure ensures unmatched efficiency for computing higher order Taylor polynomials. In particular it permits compilers to apply sophisticated vector parallelization to the derivation of nearly unmodified application code.

FUNCTIONAL DESCRIPTION: Arbogast is based on a well-defined extension of the C programming language, Modular C, and places itself between tools that proceed by operator overloading on one side and by rewriting, on the other. The approach is best described as contextualization of C code because it permits the programmer to place his code in different contexts – usual math or AD – to reinterpret it as a usual C function or as a differential operator. Because of the type generic features of modern C, all specializations can be delegated to the compiler.

- Author: Jens Gustedt
- Contact: Jens Gustedt
- Publications: Arbogast: Higher order AD for special functions with Modular C - Arbogast – Origine d'un outil de dérivation automatique
- URL: https://gforge.inria.fr/projects/arbo

6.14. CFML

Interactive program verification using characteristic formulae

KEYWORDS: Coq - Software Verification - Deductive program verification - Separation Logic

FUNCTIONAL DESCRIPTION: The CFML tool supports the verification of OCaml programs through interactive Coq proofs. CFML proofs establish the full functional correctness of the code with respect to a specification. They may also be used to formally establish bounds on the asymptotic complexity of the code. The tool is made of two parts: on the one hand, a characteristic formula generator implemented as an OCaml program that parses OCaml code and produces Coq formulae, and, on the other hand, a Coq library that provides notation and tactics for manipulating characteristic formulae interactively in Coq.

- Participants: Arthur Charguéraud, Armaël Guéneau and François Pottier
- Contact: Arthur Charguéraud
- URL: http://www.chargueraud.org/softs/cfml/

6.15. TLC

TLC Coq library

KEYWORDS: Coq - Library

FUNCTIONAL DESCRIPTION: TLC is a general purpose Coq library that provides an alternative to Coq's standard library. TLC takes as axiom extensionality, classical logic and indefinite description (Hilbert's epsilon). These axioms allow for significantly simpler formal definitions in many cases. TLC takes advantage of the type class mechanism. In particular, this allows for common operators and lemma names for all container data structures and all order relations. TLC includes the optimal fixed point combinator, which can be used for building arbitrarily-complex recursive and co-recursive definitions. Last, TLC provides a collection of tactics that enhance the default tactics provided by Coq. These tactics help constructing more concise and more robust proof scripts.

- Contact: Arthur Charguéraud
- URL: http://www.chargueraud.org/softs/tlc/

7. New Results

7.1. Automatic (Un-)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), has been published at the International Parallel and Distributed Processing Symposium (IPDPS) [15].

We are currently developing a technique to also provide good load balancing when parallelizing non-rectangular loops carrying dependences. This new technique has been called *loop uncollapsing*. The idea is to split the outermost parallel loop into two nested loops, such that the new outermost loop, when parallelized, results in well-balanced parallel threads.

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

Participants: Juan Manuel Martinez Caamaño, Manuel Selva, 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 has been more recently extended to also support loops exhibiting a non-linear behavior thanks to a modeling using “tubes”. The whole approach has been published in Concurrency and Computation: Practice and Experience [11].

7.3. Formal Proofs about Explicitly Parallel Programs with Clocks

Participants: Alain Ketterlin, Éric Violard, Tomofumi Yuki, Paul Feautrier.

We have continued this year our work on formalizing the *happens-before* relation in explicitly parallel programs of the X10 family. Our goal is to define, for certain classes of programs, a relation between instances of elementary instructions that guarantees that one instance necessarily executes before another. Our toy language includes static-control counted loops and conditionals, as well as the usual `finish` and `async` parallel constructs. Moreover, parallel activities can synchronize though the use of *clocks*, which are barriers with dynamic membership. Clocks partition the execution into phases, and profoundly modify the happens-before relation.

This year's work has focused on correctly accounting for the possibility to define specific activities that execute irrespective of the discipline of the clock in scope, so-called *detached* activities. The presence of such activities modifies the notion of phase number, because they let their instructions execute across a range of clock-phases. Our generic notion of phase *ranking* had to be modified. Similarly, the natural semantics we defined had to be slightly modified to correctly represent the parallel execution of both clocked and detached activities. In practice, almost every lemma of the Coq proof has changed, and new definitions were introduced. The new definition of happens-before preserves all desirable properties: it is correct and complete, and is a strict partial order. There is one unpleasant aspect of detached activities that had a strong impact on happens-before: the possibility of deadlocks. A significant part of new definitions and lemmas are devoted to explicit the conditions under which programs terminate. A useful outcome of this part of the mechanization is a static, compile-time deadlock detection criterion.

Most of this work has been described in a paper currently under submission (this paper will be on HAL as soon as anonymity constraints permit). However, the diversity of themes covered in this research (compilation of static-control programs, especially those that fit the polyhedral model, but also semantic modeling of explicitly parallel programs, and formal proofs) make us contemplate the redaction of a much longer paper, which we plan to start at the beginning of next year. At the same time, this work (especially the part about deadlocks) led us to start designing an happens-before relation for a language where multiple clocks can share (part of) their scopes. We hope to be able to advance the formalization of this new family of languages in the near future.

7.4. High-Performance Particle-in-Cell Simulations

Participants: Arthur Charguéraud, Yann Barsamian, Alain Ketterlin.

Yann Barsamian's PhD thesis focuses on the development of efficient programs for Particle-in-Cell (PIC) simulations, with application to plasma physics. Typically, a simulation involves a cluster of machines, each machine hosting several cores, and each core being able to execute vectorized instructions (SIMD). The challenge is to efficiently exploit these three levels of parallelism. Regarding the processing on one given multicore machine, existing algorithms either suffer from suboptimal execution time, due to sorting operations or use of atomic instructions, or suffer from suboptimal space usage. We have developed a novel parallel algorithm for PIC simulations on multicore hardware that features asymptotically-optimal memory consumption, and that does not perform unnecessary accesses to the main memory. The algorithm relies on the use of *chunk bags*, i.e., linked lists of fixed-capacity arrays, for storing particles and allowing to process them efficiently using SIMD instructions. Practical results show excellent scalability on the classical Landau damping and two-stream instability test cases. A paper was published at PPAM [12].

7.5. Granularity Control for Parallel Programs

Participant: Arthur Charguéraud.

Arthur Charguéraud contributes to the ERC DeepSea project, which is hosted at Inria Paris (team Gallium). With his co-authors, he focused this year on the development of techniques for controlling granularity in parallel programs. Granularity control is an essential problem because creating too many tasks may induce overwhelming overheads, while creating too few tasks may harm the ability to process tasks in parallel. Granularity control turns out to be especially challenging for nested parallel programs, i.e., programs in which parallel constructs such as fork-join or parallel-loops can be nested arbitrarily. This year, the DeepSea team investigated two different approaches.

The first one is based on the use of asymptotic complexity functions provided by the programmer, combined with runtime measurements to estimate the constant factors that apply. Combining these two sources of information allows to predict with reasonable accuracy the execution time of tasks. Such predictions may be used to guide the generation of tasks, by sequentializing computations of sufficiently-small size. An analysis is developed, establishing that task creation overheads are indeed bounded to a small fraction of the total runtime. These results extend prior work by the same authors [29], extending them with a carefully-designed algorithm for ensuring convergence of the estimation of the constant factors deduced from the measures, even in the face of noise and cache effects, which are taken into account in the analysis. The approach is demonstrated on a range of benchmarks taken from the state-of-the-art PBBS benchmark suite. These results were submitted to an international conference.

The second approach is based on an instrumentation of the runtime system. The idea is to process parallel function calls just like normal function calls, by pushing a frame on the stack, and only subsequently promoting these frames as threads that might get scheduled on other cores. The promotion of frames takes place at regular time interval, hence the name *heartbeat scheduling* given to the approach. Unlike in prior approaches such as *lazy scheduling*, in which promotion is guided by the work load of the system, hearbeat scheduling can be proved to induce only small scheduling overheads, and to not reduce asymptotically the amount of parallelism inherent to the parallel program. The theory behind the approach is formalized in Coq. It is also implemented through instrumented C++ programs, and evaluated on PBBS benchmarks. A paper describing this approach was submitted to an international conference.

7.6. Program verification and formal languages

Participant: Arthur Charguéraud.

- A. Charguéraud and François Pottier (Inria Paris) extended their formalization of the correctness and asymptotic complexity of the classic Union Find data structure, which features the bound expressed in terms of the inverse Ackermann function. The proof, conducted using CFML extended with time credits, was refined using a slightly more complex potential function, allowing to derive a simpler and richer interface for the data structure. This work appeared in the Journal of Automated Reasoning (JAR) [9].
- A. Charguéraud and F. Pottier have developed an extension of Separation Logic with temporary read-only permissions. This mechanism allows to temporarily convert any assertion (or "permission") to a read-only form. Unlike with fractional permissions, no accounting is required: the proposed read-only permissions can be freely duplicated and discarded. Where mutable data structures are temporarily accessed only for reading, the proposed read-only permissions enable more concise specifications and proofs. All the metatheory is verified in Coq. An article was presented at ESOP [14].
- Armaël Guéneau, PhD student advised by A. Charguéraud and F. Pottier, has developed a Coq library formalizing the asymptotic notation (big-O), and has developed an extension of the CFML verification tool to allow specifying the asymptotic complexity of higher-order, imperative programs. This new feature has been tested on several classic examples of complexity analyses, including: nested loops in $O(n^3)$ and $O(nm)$, selection sort in $O(n^2)$, recursive functions in $O(n)$ and $O(2^n)$, binary search in $O(\log n)$, and Union-Find in $O(\alpha(n))$. A paper was submitted paper to an international conference.
- A. Charguéraud has made progress towards CFML 2.0, a reimplementation of CFML entirely inside Coq. In contrast, the initial version of CFML, developed in A. Charguéraud's PhD thesis, is based on an external tool that parses OCaml source code and produces Coq axioms describing their semantics. The new version will remove the need for axioms, thereby further reducing the trusted code base. Furthermore, CFML 2.0 provides a more general memory model, designed to also accomodate formal reasoning about C-style programs, in future work. In passing, A. Charguéraud performed a complete cleanup of the TLC Coq library, which is used extensively by CFML, leading to the beta release of TLC 2.0.

- A. Charguéraud, together with Alan Schmitt (Inria Rennes) and Thomas Wood (Imperial College), developed an interactive debugger for JavaScript. The interface, accessible as a webpage in a browser, allows to execute a given JavaScript program, following step by step the formal specification of JavaScript developed in prior work on *JsCert* [31]. Concretely, the tool acts as a double-debugger: one can visualize both the state of the interpreted program and the state of the interpreter program. This tool is intended for the JavaScript committee, VM developers, and other experts in JavaScript semantics. A paper describing the tool has been submitted, and the tool has been presented to the JavaScript standardization committee (ECMA) in November 2017.

7.7. 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 Section 6.8. In previous work it has demonstrated its efficiency for a large variety of platforms.

This year, wee 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 [16]. We propose a topology-aware placement module that is based on the Hardware Locality framework, HWLOC, and that takes the characteristics of the application, of the runtime and of the architecture into account. The aim is double. On one hand we increase the abstraction and the portability of the framework, and on the other hand we enhance the performance of the model's runtime.

Within the framework of the thesis of Daniel Salas we have successfully applied ORWL to process large histopathology images. We are now able to treat such images distributed on several machines or shared in an accelerator (Xeon Phi) transparently for the user.

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. Two papers on this new research direction has been accepted this year on this topic (IMPACT 2017 workshop, HiPC 2017 conference [20]).

7.9. Parallel Polyhedral Regions

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

Nowadays best performing automatic parallelizers and data locality optimizers for static control programs rely on the polyhedral model. State-of-the-art polyhedral compilers generate only one type of parallelism when targeting multicore shared memory architectures: parallel loops via the OpenMP `omp parallel for` directive.

We propose to explore how a polyhedral compiler could exploit parallel region constructs. Instead of initializing a new set of threads each time the code enters a parallel loop and synchronizing them when exiting it, the threads are initialized once for all at the entrance of the region of interest, and synchronized only when it is necessary.

Technically, the whole region containing parallel loops is embedded in an `omp parallel` construct. Inside the parallel region, the `single` construct is used when some code needs to be executed sequentially; the `for` construct is used to distribute loop iterations between threads. Thanks to the power of the polyhedral dependence analysis, we compute when it is valid to add the optional `nowait` clause, to omit the implicit barrier at the end of a worksharing construct and thus to reduce even more control overhead.

This work was published and presented at the HiPC 2017 conference [19].

7.10. Optimization of Sparse Triangular and Banded Matrix Codes

Participants: Vincent Loechner, Rachid Seghir, Toufik Baroudi.

This work is a collaboration between Vincent Loechner and Rachid Seghir from University of Batna (Algeria). Toufik Baroudi is a second year PhD student under his supervision. Rachid Seghir was visiting the CAMUS team from March 25th to April 8th, 2017.

In this work, we enabled static polyhedral optimization techniques to handle sparse matrix storage formats. When handling sparse triangular and banded matrices in their packed formats, such as in the LAPACK library band storage, loop nests bounds and array references of the resulting codes are not affine functions. We proposed to use a new 2d-packed layout and simple affine transformations to enable polyhedral optimization of sparse triangular and banded matrix operations. The effectiveness of our proposal was shown through an experimental study over a large set of linear algebra benchmarks.

These results were published in ACM TACO [8], and will be presented at the HiPEAC conference in January 2018.

8. Bilateral Contracts and Grants with Industry

8.1. 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, which started in 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 currently working in extending Apollo to the memoization of the memory behavior for loops that are invoked several times.

8.2. 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.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. Inria Large Scale Initiative on Multicore

Philippe Clauss, Jens Gustedt, 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. The PhD defense was held December the 18th 2017.

Philippe Clauss, Jens Gustedt and Maxime Mogé are involved in the ADT Inria project ASNAP (*Accélération des Simulations Numériques pour l’Assistance Peropératoire*), in collaboration with the Inria team MIMESIS. The goal is to find opportunities in the SOFA simulation platform for applying automatic parallelization techniques developed by Camus. We are currently investigating two approaches. The first uses memory behavior memoization to generate a parallel code made of independent threads at runtime. The second uses ordered read-write locks (ORWL) to dynamically schedule a pipeline of parallel tasks.

9.1.2. ANR AJACS

Participant: Arthur Charguéraud [contact].

The AJACS research project is funded by the programme “Société de l’information et de la communication” of the ANR, from October 2014, until November 2018. http://ajacs.inria.fr/

The goal of the AJACS project is to provide strong security and privacy guarantees on the client side for web application scripts implemented in JavaScript, the most widely used language for the Web. The proposal is to prove correct analyses for JavaScript programs, in particular information flow analyses that guarantee no secret information is leaked to malicious parties. The definition of sub-languages of JavaScript, with certified compilation techniques targeting them, will allow deriving more precise analyses. Another aspect of the proposal is the design and certification of security and privacy enforcement mechanisms for web applications, including the APIs used to program real-world applications. Arthur Charguéraud focuses on the description of a formal semantics for JavaScript, and the development of tools for interactively executing programs step-by-step according to the formal semantics.

Partners: team Celtique (Inria Rennes - Bretagne Atlantique), team Prosecco (Inria Paris), team Indes (Inria Sophia Antipolis - Méditerranée), and Imperial College (London).

9.1.3. ANR Vocal

Participant: Arthur Charguéraud [contact].

The Vocal research project is funded by the programme “Société de l’information et de la communication” of the ANR, for a period of 48 months, starting on October 1st, 2015. https://vocal.lri.fr/

The goal of the Vocal project is to develop the first formally verified library of efficient general-purpose data structures and algorithms. It targets the OCaml programming language, which allows for fairly efficient code and offers a simple programming model that eases reasoning about programs. The library will be readily available to implementers of safety-critical OCaml programs, such as Coq, Astrée, or Frama-C. It will provide the essential building blocks needed to significantly decrease the cost of developing safe software. The project intends to combine the strengths of three verification tools, namely Coq, Why3, and CFML. It will use Coq to obtain a common mathematical foundation for program specifications, as well as to verify purely functional components. It will use Why3 to verify a broad range of imperative programs with a high degree of proof automation. Finally, it will use CFML for formal reasoning about effectful higher-order functions and data structures making use of pointers and sharing.

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

Partners: team Gallium (Inria Paris), team DCS (Verimag), TrustInSoft, and OCamlPro.

9.2. European Initiatives

9.2.1. FP7 & H2020 Projects

Project acronym: ERC Deepsea

Project title: Parallel dynamic computations

Duration: Jun. 2013 - May 2018

Coordinator: Umut A. Acar

Other partners: Carnegie Mellon University

Abstract:

The objective of this project is to develop abstractions, algorithms and languages for parallelism and dynamic parallelism with applications to problems on large data sets. Umut A. Acar (affiliated to Carnegie Mellon University and Inria Paris - Rocquencourt) is the principal investigator of this ERC-funded project. The other main researchers involved are Mike Rainey (Inria, Gallium team), who is full-time on the project, and Arthur Charguéraud (Inria, Toccata Camus), who works part time on this project. Project website: http://deepsea.inria.fr/.

9.3. International Initiatives

9.3.1. Inria International Partners

9.3.1.1. 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
- Carnegie Mellon University, Pittsburgh, USA
- Indian Institute of Science (IIIS) Bangalore, India
- Barcelona Supercomputing Center, Barcelona, Spain

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Selection

10.1.1.1. Member of the Conference Program Committees

Philippe Clauss and Cédric Bastoul have been part of the program committee of IMPACT 2017 and 2018 (International Workshop on Polyhedral Compilation Techniques), held in conjunction with the international conference HiPEAC.

Cédric Bastoul has been part of the program committee of the international conference on Compiler Construction 2017 and 2018 (CC'2017 and CC'2018).

Cédric Bastoul and Vincent Loechner have been part of the program committee of the HIP3ES workshop 2017 and 2018 (International Workshop on High Performance Energy Efficient Embedded Systems), co-organized by Cédric Bastoul in conjunction with the international conference HiPEAC.

Arthur Charguéraud has been part of the program committee for the Conference on Verified Software: Theories, Tools, and Experiments (VSTTE 2017).

10.1.1.2. Reviewer

Philippe Clauss has been reviewer for the following conferences and workshops: IMPACT 2017 and 2018 (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 and 2018 (International Conference on Compiler Construction), PARMA 2017 (International Workshop on Parallel Programming and Run-Time Management Techniques for Many-core Architectures), IMPACT 2017 and 2018 (International Workshop on Polyhedral Compilation Techniques), HIP3ES 2017 and 2018 (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: Journal of Computer and System Sciences, Journal of Software: Practice and Experience, IEEE Transactions on Computers.

Cédric Bastoul has been reviewer for the following journals: Journal of Parallel, Emergent and Distributed Systems, and IEEE Transactions on Computers.

Arthur Charguéraud has been reviewer for JAR (Journal of Automated Reasoning), DMTCS (journal of Discrete Mathematics and Theoretical Computer Science), and JFP (Journal of Functional Programming).

Vincent Loechner has been reviewer for: JAR (Journal of Automated Reasoning, Springer), STTT (Int. J. on Software Tools for Technology Transfer, Springer), ComCom (Computer Communications, Elsevier).

10.1.3. Invited Talks

Philippe Clauss has been invited to give a talk at a seminar dedicated to Jean-Luc Gaudiot, organized by the French Computer Science Engineering school ENSIEE, Paris, September the 21st 2017. The topic of his talk was: *Le modèle polyédrique au delà de la compilation statique, des fonctions affines et des boucles*.

Arthur Charguéraud has been invited to give a talk at ENS Rennes, on November 21st, 2017, to present the CFML interactive program verification tool.

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.

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 and serves as co-editor of the standards document. 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.

In 2017, he was the one of the main forces behind the elaboration of C17, the new version of the C standard that is expected to go into ballot in the member states end of 2017.

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

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

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

Master : Jens Gustedt, parallélisme, 14h, M1, Université de Strasbourg, France

IUT d'Informatique : Alain Ketterlin, Architecture et programmation des mécanismes de base d'un système informatique, 68h, Université de Strasbourg, France

Licence : Alain Ketterlin, Algorithmique et programmation L1, 82h, Université de Strasbourg, France

Master (Informatique) : Alain Ketterlin, Ingénierie de la preuve en Coq, 18h, Université de Strasbourg, France

Master (Calcul Scientifique et Mathématiques de l'Information) : Alain Ketterlin, Compilation et optimisation, 26h, Université de Strasbourg, France

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

Licence : Cédric Bastoul, Concurrent Systems, 20h, L3, Université de Strasbourg, France

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

Master : Cédric Bastoul, Parallelism, 19h, M1, Université de Strasbourg, France

Master : Cédric Bastoul, Introduction to Research, 11h, L2+M1, Université de Strasbourg, France

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

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

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

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

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

Licence : Eric Violard, Systèmes Concurrents (licence informatique), 7h eq. TD, L3, Université de Strasbourg, France

Master : Arthur Charguéraud, Proof of Programs (MPRI), 12h, M2, Université Paris Diderot, France

Licence : Vincent Loechner, responsable pédagogique de la licence professionnelle SIL spécialité ARS (Administration de Réseaux et Services), 24h, L3, université de Strasbourg, France

Licence : Vincent Loechner, systèmes d'exploitation, 13h, L2, université de Strasbourg, France

Licence : Vincent Loechner, administration système et internet, 54h, L3, université de Strasbourg, France

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

Master : Vincent Loechner, OS embarqués, 34h, M2, université de Strasbourg, France

Master : Vincent Loechner, calcul parallèle, 30h, 3ième année école d'ingénieur (TPS), université de Strasbourg, France

10.2.2. Supervision

PhD: Nabil Hallou, *Dynamic binary optimizations*, University of Rennes, December the 18th 2017, Erven Rohou (PACAP team) and Philippe Clauss

PhD in progress: Salwa Kobeissi, *Dynamic parallelization of recursive functions by transformation into loops*, September 2017, Philippe Clauss

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: Yann Barsamian, *Optimization and parallelization of particle and semi-Lagrangian methods for multi species plasma simulations*, since Oct 2014, Eric Violard.

PhD in progress: Armaël Géneau, *Formal verification of complexity analyses*, since Sept 2016, co-advised by Arthur Charguéraud and François Pottier, from team Gallium (Inria Paris), where Armaël is located.

PhD in progress: Harenome Ranaivoarivony-Razanajato, *Hierarchical Parallelization and Optimization*, Oct. 2016, Cédric Bastoul and Vincent Loechner

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 a Graphical Pipeline for Professionnal Inkjet Printing*, Jun. 2016, Cédric Bastoul and Vincent Loechner

10.2.3. Juries

Philippe Clauss participated to the following PhD committees in 2017:

Date	**Candidate**	**Place**	**Role**
Dec. 11	Alexandre Maréchal	Université de Grenoble	Examiner
Dec. 18	Nabil Hallou	Université de Rennes	Co-advisor
Dec. 21	Jordy Ruiz	Université de Toulouse	Reviewer

Vincent Loechner participated as examiner to the PhD committee of Maroua Maalej, defended on Sept. 26th 2017 at Université Claude Bernard (Lyon 1).

10.3. Popularization

A. Charguéraud is one of the three organizers of the *Concours Castor informatique*http://castor-informatique.fr/. The purpose of the Concours Castor in to introduce pupils (from *CM1* to *Terminale*) to computer sciences. More than 500,000 teenagers played with the interactive exercises in November 2017.

Jens Gustedt is 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.

Cédric Bastoul prepared activities and participated to *Fête de la Science* at University of Strasbourg in October 2017.

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Major publications by the team in recent years

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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:

A1.5.1. - Systems of systems
A3.1.1. - Modeling, representation
A3.2.2. - Knowledge extraction, cleaning
A3.2.5. - Ontologies
A6.1.5. - Multiphysics modeling

Other Research Topics and Application Domains:

B1.1.1. - Structural biology
B1.1.2. - Molecular biology
B1.1.9. - Bioinformatics
B2.2.1. - Cardiovascular and respiratory diseases
B2.2.4. - Infectious diseases, Virology

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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 may be considered to encode the blueprint for life, whereas proteins and RNA 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], [51].

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 RNA molecules, 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], [41]. 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 [45], [71]. Therefore, developing techniques which can mine knowledge of protein structures and their interactions is an important way to enhance our knowledge of biology [30].

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 [48]. The latest version of Kpax [9] 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) [39].

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 [42] developed by the Human Genome Organization (HUGO) mostly address the experimental wet lab aspects leading to data production and curation [53]. A different point of view is represented in the Interaction Network Ontology (INO), a community-driven ontology that aims to standardise and integrate data on interaction networks and to support computer-assisted reasoning [73]. 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" [38], 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) [29] 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 developed a recommender-based data mining technique to associate enzyme classification code numbers with Pfam domains using our recently developed EC-DomainMiner program [11]. We subsequently generalised this approach as a tripartite graph mining method for inferring associations between different protein annotation sources, which we call "CODAC" (for COmputational Discovery of Direct Associations using Common Neighbours). A first paper on this approach was presented at IWBBIO-2017 [23].

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 [44]

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

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 [10], [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], [46], 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 considerably [10], [61]. 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 [28], [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 [8], and was subsequently applied to several symmetrical complexes from the “CAPRI” blind docking experiment [18]. 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 [52], [37], [49], [50]. 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 [27]. 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 [43]. 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.

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. We wish to proceed firstly by putting more emphasis on the single-body terms in the scoring function [35], 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], David Ritchie, Sabeur Aridhi, Gabin Personeni, Seyed Ziaeddin Alborzi, Bishnu Sarker, Claire Lacomblez.

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 [54], [55]. 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). This approach has also been applied using pattern structure mining (an extension of formal concept analysis) of drug and disease ontologies to discover frequently associated adverse drug events in patients [20]. This work was performed in collaboration with the Centre for BioMedical Informatics Research (BMIR) at Stanford University.

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 [34]. 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 [26]. 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 [40], [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 Lorraine Université d’Excellence (LUE) “CITRAM” project 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 [14].

4.3. Protein-RNA Interactions

Participants: Isaure Chauvot de Beauchêne [contact person], Bernard Maigret, Maria Elisa Ruiz Echartea, David Ritchie.

As well as playing an essential role in the translation of DNA into proteins, RNA molecules carry out many other essential biological functions in cells, often through their interactions with proteins. A critical challenge in modelling such interactions computationally is that the RNA is often highly flexible, especially in single-stranded (ssRNA) regions of its structure. These flexible regions are often very important because it is through their flexibility that the RNA can adjust its 3D conformation in order to bind to a protein surface. However, conventional protein-protein docking algorithms generally assume that the 3D structures to be docked are rigid, and so are not suitable for modeling protein-RNA interactions. There is therefore much interest in developing protein-RNA docking algorithms which can take RNA flexibility into account.

We are currently developing a novel flexible docking algorithm which first docks small fragments of ssRNA (typically three nucleotides at a time) onto a protein surface, and then combinatorially reassembles those fragments in order to recover a contiguous ssRNA structure on the protein surface [33], [32]. We have since implemented a prototype “forward-backward” dynamic programming algorithm with stochastic backtracking that allows us to model protein RNA interactions for ssRNAs of up to 7 nucleotides without requiring any prior knowledge of the interaction, while still avoiding a brute-force search. In the frame of our PEPS collaboration “InterANRIL” with the IMoPA lab (Univ de Lorraine), we are currently working with biologists to apply the approach to modeling certain long non-coding RNA (lncRNA) complexes. We next plan to build a large library of RNA fragments in order to extend this approach to partially structured RNA molecules, and in the longer term we aim to apply this approach to modeling flexible peptide-protein interactions in a similar way.

5. Highlights of the Year

5.1. Highlights of the Year

Following a collaboration with Emmanuel Levy at the Weizmann Institute, a manuscript on annotating protein quaternary structures using our Kpax software has been published in Nature Methods [16].

6. New Software and Platforms

6.1. Hex

KEYWORDS: 3D rendering - Bioinformatics - 3D interaction - Structural Biology
SCIENTIFIC DESCRIPTION: Hex is an interactive protein docking and molecular superposition program for Linux Mac-OS and Windows-XP. Hex understands protein and DNA structures in PDB format, and it can also read small-molecule SDF files. 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).
FUNCTIONAL DESCRIPTION: The underlying algorithm uses a novel polar Fourier correlation technique to accelerate the search for close-fitting orientations of the two molecules.

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

6.2. Kbdock

KEYWORD: 3D interaction
SCIENTIFIC DESCRIPTION: Kbdock is a database of 3D protein domain-domain interactions with a web interface.
FUNCTIONAL DESCRIPTION: The Kbdock database is built from a snapshot of the Protein Databank (PDB) in which all 3D structures are cut into domains according to the Pfam domain description. A web interface allows 3D domain-domain interactions to be compared by Pfam family.

- 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: Kpax is a program for aligning and superposing the 3D structures of protein molecules.
FUNCTIONAL DESCRIPTION: The algorithm uses a Gaussian representation of the protein backbone in order to construct a similarity score based on the 3D overlap of the Gaussians of the proteins to be superposed. Multiple proteins may be aligned together (multiple structural alignment) and databases of protein structures may be searched rapidly.

- Participant: David Ritchie
- Contact: David Ritchie

6.4. Sam

Protein Symmetry Assembler

KEYWORDS: Proteins - Structural Biology
SCIENTIFIC DESCRIPTION: Sam is a program for making symmetrical protein complexes, starting from a single monomer.
FUNCTIONAL DESCRIPTION: The algorithm searches for good docking solutions between protein monomers using a spherical polar Fast Fourier transform correlation in which symmetry restraints are built into the calculation. Thus every candidate solution is guaranteed to have the desired symmetry.

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

6.5. gEMfitter

KEYWORDS: 3D reconstruction - Cryo-electron microscopy - Fitting
SCIENTIFIC DESCRIPTION: A program for fitting high resolution 3D protein structures into low resolution cryo-EM density maps.
FUNCTIONAL DESCRIPTION: A highly parallel fast Fourier transform (FFT) EM density fitting program which can exploit the special hardware properties of modern graphics processor units (GPUs) to accelerate both the translationnal and rotational parts of the correlation search.

- Authors: Van-Thai Hoang and David Ritchie
- Contact: David Ritchie
- URL: http://gem.loria.fr/gEMfitter/

6.6. ECDM

ECDomainMiner
KEYWORD: Functional annotation
SCIENTIFIC DESCRIPTION: EC-DomainMiner uses a recommender-based approach for associating EC (Enzyme Commission) numbers with protein Pfam domains from EC-sequence relationships that have been annotated previously in the SIFTS and Uniprot databases.
FUNCTIONAL DESCRIPTION: A program to associate protein Enzyme Commission numbers with Pfam domains

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

6.7. GODM

GO-DomainMiner
KEYWORD: Functional annotation
FUNCTIONAL DESCRIPTION: GO-DomainMiner is is a graph-based approach for associating GO (gene ontology) terms with protein Pfam domains.

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

6.8. BLADYG

A Block-centric graph processing framework for LArge Dynamic Graphs
KEYWORDS: Distributed computing - Dynamic graph processing

FUNCTIONAL DESCRIPTION: BLADYG is a block-centric framework that addresses the issue of dynamism in large-scale graphs. BLADYG starts its computation by collecting the graph data from various data sources. After collecting the graph data, BLADYG partitions the input graph into multiple partitions. Each BLADYG worker loads its block/partition and performs both local and remote computations, after which the status of the blocks is updated. The BLADYG coordinator orchestrates the execution of the considered graph operation in order to deal with graph updates.

- Partner: University of Trento
- Contact: Sabeur Aridhi

6.9. Platforms

6.9.1. 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). In 2017, a Galaxy portal (https://galaxyproject.org/) for structural bioinformatics software was added to the platform thanks to funding for an engineer (Antoine Chemardin) from the IFB.

- Contact: Marie-Dominique Devignes

7. New Results

7.1. Drug Targeting and Adverse Drug Side Effects

Identifying new molecular targets using comparative genomics and knowledge of disease mechanisms is a rational first step in the search for new preventative or therapeutic drug treatments [47]. We are mostly concerned with three global health problems, namely fungal and bacterial infections and hypertension. Through on-going collaborations with several Brasilian laboratories (at University of Mato Grosso State, University of Maringá, Embrapa, and University of Brasilia), we previously identified several novel small-molecule drug leads against *Trypanosoma cruzi*, a parasite responsible for Chagas disease [72]. With the University of Maringá, we subsequently found several active molecules against the flavoenzyme TRR1 in *Candida albicans*, and two manuscripts are in preparation. We also proposed several small-molecule inhibitors against *Fusarium graminearum*, a fungal threat to global wheat production [47], [31]. Two further manuscripts on this topic are currently in preparation. Concerning hypertension, we continued our collaboration with Prof. Catherine Llorens-Cortes at Collège de France to study the interaction between the apelin receptor (a transmembrane protein important for blood pressure regulation) and the aminopetidase A enzyme [15].

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 Adrien Coulet (Orpailleur team co-supervisor of Gabin Personeni) and Prof. Michel Dumontier (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 [57], [56]. A paper describing this work has been published in the Journal of Biomedical Semantics [20].

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 [8]. An article describing the results obtained when using Sam to dock several symmetrical protein complexes from the “CASP/CAPRI” docking experiment has also been published [18]. This study showed that many of the models of protein structures built by members of the “CASP” fold prediction community are “dockable” in the sense that Sam is able to find acceptable docking solutions from amongst the CASP models.

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. The latest version of our “Kpax” protein structure alignment algorithm can flexibly align pairs of structures that cannot be completely superposed by a single rigid-body transformation, and can calculate multiple alignments of several similar structures flexibly [9]. In collaboration with Alain Hein of the INRA lab “Agronomie et Environnement”, we used Kpax to help study the structures of various “Cyp450” enzymes in plants [21]. In collaboration with Emmanuel Levy of the Weizmann Institute, we used Kpax to superpose and compare all of the symmetrical protein complexes in the Protein Databank in order to verify or remediate their quaternary structure annotations. A manuscript describing this work has been published in Nature Methods [16].

7.4. Large-Scale Annotation of Protein Domains and Sequences

Many protein chains in the Protein Data Bank (PDB) are cross-referenced with Pfam domains and Gene Ontology (GO) terms. However, these annotations do not explicitly indicate any relation between EC numbers and Pfam domains, and many others lack GO annotations. In order to address this limitation, as part of the PhD thesis project of Seyed Alborzi, we developed the CODAC approach for mining multiple protein data sources (i.e. SwissProt, TremBL, and SIFTS) in order to associate GO molecular function terms with Pfam domains, for example. We named the software implementation “GO-DomainMiner”. This work was first presented at IWBBIO 2017 [23]. A full paper has been submitted to a special issue of *BMC Bioinformatics*, and is now in review. In collaboration with Maria Martin’s team at the European Bioinformatics Institute (EBI), we combined the CODAC approach with a novel combinatorial association rule based approach called “CARDM” for annotating protein sequences. When applied to the large Uniprot/TrEMBL sequence database of 63 million protein entries, CARDM predicted over 24 million EC numbers and 188 million GO terms for those entries. A journal paper in collaboration with the EBI on comparing the quality of these predicted annotations with other state of the art annotation methods is in preparation, and a poster was presented at ISMB-ECCB-2017 [24].

7.5. Distributed Protein Graph Processing

The huge number of protein sequences in protein databases such as UniProtKB calls for rapid procedures to annotate them automatically. We are using existing protein annotations to predict the annotations of new or non-reviewed proteins. In this context, we developed the “DistNBLP” method for annotating protein sequences using a graph representation and a distributed label propagation algorithm. DistNBLP uses the BLADYG framework [12] to process protein graphs on multiple compute nodes by applying a neighbourhood-based label propagation algorithm in a distributed way. We applied DistNBLP in the recent “CAFA 3” (critical Assessment of Protein Function Annotation) community experiment to annotate new protein sequences automatically. This work was presented as a poster at ISMB/ECCB-2017 [22]. We are also interested in feature selection for subgraph patterns. In collaboration with the LIMOS laboratory at Université Clermont Auvergne we also developed a scalable approach using MapReduce for identifying sub-graphs having similar labels in very large graphs [17].

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. CPER – IT2MP

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

Project title: *Innovations Technologiques, Modélisation et Médecine Personnalisée*; PI: Faiez Zannad, Univ Lorraine (Inserm-CHU-UL). Value: 14.4 M€ ("SMEC" platform – Simulation, Modélisation, Extraction de Connaissances – coordinated by Capsid and Orpailleur teams for Inria Nancy – Grand Est, with IECL and CHRU Nancy: 860 k€, approx); Duration: 2015–2020. Description: The IT2MP project emcompasses four interdisciplinary platforms that support several scientific pôles of the university whose research involves human health. The SMEC platform supports research projects ranging from molecular modeling and dynamical simulation to biological data mining and patient cohort studies.

8.1.2. LUE – CITRAM

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

Project title: *Conception d'Inhibiteurs du Transfert de Résistances aux agents Anti-Microbiens: bio-ingénierie assistée par des approches virtuelles et numériques, et appliquée à une relaxase d'élément conjugatif intégratif*; PI: N. Leblond, Univ Lorraine (DynAMic, UMR 1128); Other partners: Chris Chipot, CNRS (SRSMSC, UMR 7565); Value: 200 k€ (Capsid: 80 k€); Duration: 2017–2018. Description: This project follows on from the 2016 PEPS project "MODEL-ICE". 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, and to develop small-molecule inhibitors of these interactions.

8.1.3. PEPS – DynaCriGalT

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

Project title: *Criblage virtuel et dynamique moléculaire pour la recherche de bio-actifs ciblant la β4GalT7, une enzyme de biosynthèse des glycosaminoglycanes*; PI: I. Chauvot de Beauchêne, Capsid (Inria Nancy – Grand Est); Partners: Sylvie Fournel-Gigleux, INSERM (IMoPA, UMR 7365); Value: 15 k€; Duration: 2017–2018. Description: The β4GalT7 glycosyltransferase initiates the biosynthesis of glycosaminoglycans (GAGs), and is a therapeutical target for small molecules which might correct a defect in the synthesis and degradation of GAGs in rare genetic diseases. Classical approaches to propose active molecules have failed for this target. The DynaCriGalT project combines molecular dynamics modelling of the GAG active site with virtual screening in order to propose a diverse set of small molecules for *in vitro* compound testing.

8.1.4. PEPS – InterANRIL

Participant: Isaure Chauvot de Beauchêne [contact person].

Project title: *Identification et modélisation des interactions nécessaires à l'activité du long ARN non-codant ANRIL dans la régulation épigénétique des gènes*; PI: Sylvain Maenner, Univ Lorraine (IMoPA, UMR 7365); Value: 20 k€; Duration: 2017–2018. Description: ANRIL is a long non-coding RNA (lncRNA) which has been identified as an important factor in the susceptibility cardiovascular diseases. ANRIL is involved in the epigenetic regulation of the expression of a network of genes via mechanisms that are still largely unknown. This project aims to identify and model the protein-RNA and/or DNA-RNA interactions that ANRIL establishes within the eukaryotic genome.

8.2. National Initiatives

8.2.1. FEDER – SB-Server

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

Project title: *Structural bioinformatics server*; PI: David Ritchie, Capsid (Inria Nancy – Grand Est); Value: 24 k€; Duration: 2015–2020. Description: This funding provides a small high performance computing server for structural bioinformatics research at the Inria Nancy – Grand Est centre.

8.2.2. ANR

8.2.2.1. Fight-HF

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

Project title: *Combattre l'insuffisance cardiaque*; PI: Patrick Rossignol, Univ Lorraine (FHU-Cartage); Partners: multiple; Value: 9 m€ (Capsid and Orpailleur: 450 k€, approx); Duration: 2015–2019. Description: This "Investissements d'Avenir" 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.

Project title: *Institut Français de Bioinformatique*; PI: Jean-François Gibrat (CNRS UMS 3601); Partners: multiple; Value: 20 M€ (Capsid: 126 k€); Duration: 2014–2021. Description: 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.

8.3. International Initiatives

8.3.1. Informal International Partners

Participant: David Ritchie; Project: *Integrative Modeling of 3D Protein Structures and Interactions;* Partner: Rocasolano Institute of Physical Chemistry, Spain. Funding: Inria Nancy – Grand Est ("Nancy Emerging Associate Team").

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.

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

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

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

8.4. International Research Visitors

8.4.1. Visits of International Scientists

8.4.1.1. Internships

Isis Grenier Capoci from the State University of Maringá, Brasil visited the team (through the programme "Doutorado Sanduiche no Exterior") to develop new inhibitors of *Candida albicans* TRR1 under the supervision of Bernard Maigret.

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).

Marie-Dominique Devignes organised a workshop on "Security issues in health data processing" for the Fédération Charles Hermite, Nancy.

Sabeur Aridhi co-chaired the workshop on "Large scale time-dependent graphs" (TD-LSG) as part of ECML-PKDD-2017.

9.1.1.2. Member of Organizing Committees

David Ritchie participated in the organisation of GGMM-2017 (Reims).

9.1.2. Scientific Events Selection

9.1.2.1. Member of the Conference Program Committees

David Ritchie was a member of the programme committee for GGMM-2017, Reims.

Sabeur Aridhi was a member of the programme committee for TDLSG/ECML-PKDD, Skopje, Macedonia.

9.1.2.2. Reviewer

Marie-Dominique Devignes was a reviewer for IWBBIO, NETTAB, KDIR, and BIBM.

David Ritchie was a reviewer for IJCAI and JOBIM.

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

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

Sabeur Aridhi is a member of the editorial board of Intelligent Data Analysis.

9.1.3.2. Reviewer - Reviewing Activities

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

9.1.4. Invited Talks

David Ritchie gave a presentation at the Unité de Mathématiques et Informatique Appliquées de Toulouse (MIAT).

9.1.5. Scientific Expertise

Marie-Dominique Devignes reviewed grant applications for the Institut Pasteur and the Institut de Recherche en Santé Publique (IRESP).

Sabeur Aridhi reviewed grant applications for the French Committee for the Evaluation of Academic and Scientific Cooperation with Brazil (COFECUB).

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

Marie-Dominique Devignes participated in a Recruitment Committee for a MdC at Univ Lille.

9.1.6. 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.

Isaure Chauvot de Beauchêne is an elected member of the scientific council of the AM2I (Automatique, Mathématiques, Informatiques et leurs Interactions) pole of the University of Lorraine.

Sabeur Aridhi is responsible for the major in IAMD (Ingénierie et Applications des Masses de Données) at TELECOM Nancy (Univ. Lorraine), and a member of the “Commission du Développement Technologique” recruitment committee at Inria Nancy – Grand Est.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

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

Licence: Sabeur Aridhi, *Databases,* 82 hours, L1, Univ Lorraine.

Licence: Sabeur Aridhi, *Massive Data Management,* 68 hours, L2, Univ Lorraine.

Licence: Sabeur Aridhi, *Big Data Hackathon,* 8 hours, L3, Univ Lorraine.

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

Licence: Isaure Chauvot de Beauchêne, *TD Bioinformatique et Modelisation,* 10 hours, L3, Univ Lorraine.

Doctorat: Isaure Chauvot de Beauchêne, *Bioinformatics and Visualisation,* 10 hours, M1–PhD, ISCD (Institute for Computing and Data Sciences) Summer School, Roscoff.

9.2.2. Supervision

PhD in progress: Bishnu Sarker, *Developing distributed graph-based approaches for large-scale protein function annotation and knowledge discovery,* 01/11/2017, David Ritchie, Sabeur Aridhi.

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

PhD in progress: Gabin Personeni, *Apport des ontologies de domaines pour l’extraction de connaissances à partir de données biomédicales,* 01/10/2014, Marie-Dominique Devignes, Adrien Coulet.

PhD in progress: Seyed Ziaeddin Alborzi, *Automatic discovery of hidden associations using vector similarity: application to biological annotation prediction,* 01/10/2014, David Ritchie, Marie-Dominique Devignes.

9.2.3. Juries

Bernard Maigret was a “rapporteur” for the PhD thesis of N. Madeleine, *Recherche d’inhibiteurs de l’interaction Lu–Laminine par des techniques de modélisation et de la simulation moléculaire,* Université de La Réunion, 18/09/2017 (PhD supervisor Dr F. Gardebien).

9.3. Popularization

The team presented its activities during the Inria Nancy – Grand Est centre’s Open Day for the “Fête de la Science 2017” (14 Oct 2017).

10. Bibliography

Major publications by the team in recent years

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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

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Project-Team CARAMBA

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

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A4.3.1. - Public key cryptography
A4.3.2. - Secret key cryptography
A4.8. - Privacy-enhancing technologies
A6.2.7. - High performance computing
A7.1. - Algorithms
A8.4. - Computer Algebra
A8.5. - Number theory
A8.10. - Computer arithmetic

Other Research Topics and Application Domains:

B8.5. - Smart society
B9.4.1. - Computer science
B9.4.2. - Mathematics
B9.8. - Privacy

1. Personnel

Research Scientists

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Jérémie Detrey [Inria, Researcher]
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Aurore Guillevic [Inria, Researcher]
Pierre-Jean Spaenlehauer [Inria, Researcher]
Paul Zimmermann [Inria, Senior Researcher, HDR]

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

External Collaborator

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Svyatoslav Covanov [Univ. Lorraine]
Laurent Grémy [Univ. Lorraine, until Aug 2017]
Andrianina Sandra Rasoamiaramanana [Univ. Lorraine and Orange, from May 2017]
Paul Huynh [Univ. Lorraine, from Oct 2017]

Post-Doctoral Fellows

Enea Milio [Inria, until Aug 2017]
Shashank Singh [Inria, until Sep 2017]

Administrative Assistants

Emmanuelle Deschamps [Inria]
Virginie Priester [CNRS]

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.

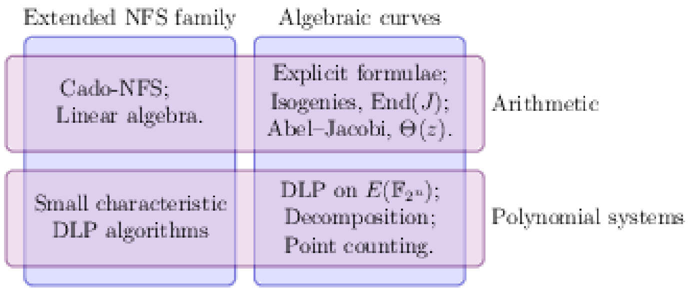

Figure 1. Visual representation of the thematic organization of CARAMBA.

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.

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 industry [40], [25].

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 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 [27], [35], [34], [32]. A stream of computational records have been obtained since 2013 with 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 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.

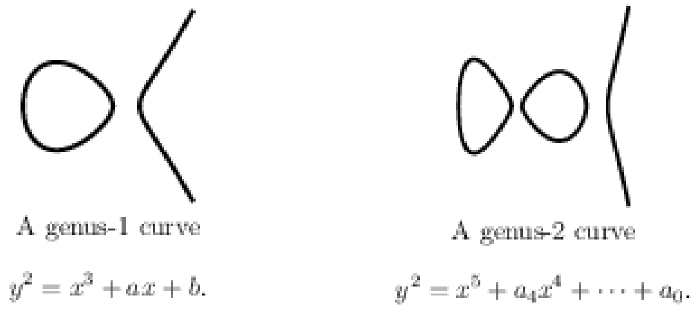

Figure 2.

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 [38]. 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 [31].

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 [41] (for a glimpse of some of the reactions within the academic community, the reference [37] 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 [24].

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 work plan 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 [38].

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 advanced 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. Symmetric Cryptography

Since the recruiting of Marine Minier in September 2016 as a Professor at Université of Lorraine, a new research domain has emerged in the CARAMBA team: symmetric key cryptology. The aim is to design and analyze symmetric key cryptographic primitives focusing on the following particular aspects:

- the use of constraint programming for the cryptanalysis, especially of block ciphers and the AES standard;
- the design of lightweight cryptographic primitives well-suited for constraint environment such as micro-controllers, wireless sensors, etc.
- white-box cryptography and software obfuscation methods to protect services execution on dedicated platforms.

3.5. 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 [30], [29].

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 6.2, 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.
- The recent hiring of Minier is likely to lead the team to study particular polynomial systems in contexts 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 [30], [29]. 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.

[0] In [25], the minimal recommended RSA key size is 2048 bits for usage up to 2030. See also Annex B, in particular Section B.1 “Records de calculs cryptographiques”.

[0] The work [36] is one of only two academic works cited by NIST in the initial version (2011) of the report [40].

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 [24] 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.

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 team organized 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.

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 verifiablity relies on the fact that the ballot box is public (voters can check that their ballots have been received) 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.

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

6.2. tinygb

KEYWORD: Gröbner bases
FUNCTIONAL DESCRIPTION: Tinygb is a free software which implements tools for computing Gröbner bases with Faugère's F4 algorithm.
NEWS OF THE YEAR: The code has been largely rewritten and optimized. A new release is planned for the beginning of 2018.

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

6.3. CADO-NFS

Crible Algébrique: Distribution, Optimisation - Number Field Sieve
KEYWORDS: Cryptography - Number theory
FUNCTIONAL DESCRIPTION: CADO-NFS is a complete implementation in C/C++ of the Number Field Sieve (NFS) algorithm for factoring integers and computing discrete logarithms in finite fields. It consists in various programs corresponding to all the phases of the algorithm, and a general script that runs them, possibly in parallel over a network of computers.

- Participants: Pierrick Gaudry, Emmanuel Thomé and Paul Zimmermann
- Contact: Emmanuel Thomé
- URL: http://cado-nfs.gforge.inria.fr/

7. New Results

7.1. Improved Complexity Bounds for Counting Points on Hyperelliptic Curves

Participants: Simon Abelard, Pierrick Gaudry, Pierre-Jean Spaenlehauer.

In [16], we present a probabilistic Las Vegas algorithm for computing the local zeta function of a hyperelliptic curve of genus g defined over $\mathbb{F}_q$. It is based on the approaches by Schoof and Pila combined with a modeling of the ℓ-torsion by structured polynomial systems. Our main result improves on previously known complexity bounds by showing that there exists a constant $c > 0$ such that, for any fixed g, this algorithm has expected time and space complexity $O((\log q)^{cg})$ as q grows and the characteristic is large enough.

7.2. Deciphering of a Code Used by a 19th Century Parisian Violin Dealer

Participant: Pierrick Gaudry.

This paper [4] is joint work with Jean-Philippe Échard, Curator at the Cité de la Musique, Paris.

The study of three ledgers from the archives of a prominent Parisian violin maker's workshop (active from 1796 to 1948) reveals that some of their content was encrypted. We present the deciphering of the code, and a discussion of its use in the context of the workshop. Charles-Adolphe Gand introduced this code around 1847 to encrypt values of antique/used violins he would buy and resell. His successors maintained the use of this code at least until 1921. Taking a few examples of instruments by Stradivari and other violin makers, we illustrate how the decoded ledgers – listing transactions for more than 2,500 instruments – are of high interest as historical sources documenting the margins, rebates, and commercial practices of these violin dealers. More generally, we contribute to better describing the evolution of the market for antique instruments of the violin family.

7.3. Discrete Logarithm Record Computation in Extension Fields

Participants: Laurent Grémy, Aurore Guillevic, Emmanuel Thomé.

Together with F. Morain from the GRACE team, we reached new record sizes for the discrete logarithm problems over non-prime finite fields of small extension degrees [19], [8]. Assessing the hardness of the discrete logarithm problem in such fields is highly relevant to the security of cryptographic pairings. Our computations are not terribly large computations compared to other record-size computations for integer factoring or discrete logarithm over prime fields, but on the other hand more novelty is present in these contexts: use of automorphisms, higher degree sieving, for example.

Further research in this direction is needed, especially regarding the effectiveness of the variants of the "tower" number field sieve variants.

Furthermore, A. Guillevic and L. Grémy have gathered in a database all published records of discrete logarithm computations in all kinds of finite fields. The database is hosted on gitlab and is open to external contributions. A web interface for browsing the database is available at http://perso.ens-lyon.fr/laurent.gremy/dldb/index.html.

7.4. Using Constraint Programming to Solve a Cryptanalytic Problem

Participant: Marine Minier.

In [7], we describe Constraint Programming (CP) models to solve a cryptanalytic problem: the related key differential attack against the standard block cipher AES. We show that CP solvers are able to solve these problems quicker than dedicated cryptanalysis tools, and we prove that the 11 rounds solution on AES-192 claimed to be optimal is wrong. Instead, we provide the best related key differential characteristic on 10 rounds of AES-192. We also improved the related-key distinguisher and the basic related-key differential attack on the full AES-256 by a factor 2^6 and the q-multicollisions by a factor 2.

7.5. Optimized Binary64 and Binary128 Arithmetic with GNU MPFR

Participant: Paul Zimmermann.

Together with Vincent Lefèvre (ARIC team, Inria Rhône-Alpes), Paul Zimmermann wrote an article "Optimized Binary64 and Binary128 Arithmetic with GNU MPFR", and presented it at the 24th IEEE Symposium on Computer Arithmetic [9]. This article describes algorithms used to optimize the GNU MPFR library when the operands fit into one or two words. On modern processors, a correctly rounded addition of two quadruple precision numbers is now performed in 22 cycles, a subtraction in 24 cycles, a multiplication in 32 cycles, a division in 64 cycles, and a square root in 69 cycles. It also introduces a new faithful rounding mode, which enables even faster computations. These optimizations will be available in version 4 of MPFR.

7.6. A New Measure for Root Optimization

Participants: Nicolas David, Paul Zimmermann.

In the General Number Field Sieve (GNFS) for integer factorization or discrete logarithm, the first stage is polynomial selection. Polynomial selection itself consists in two steps: size-optimization and root-optimization. The classical measures used to rank polynomials during the root-optimization are the so-called α and Murphy-E values. During the internship of Nicolas David, it was shown that these classical measures might be off by up to 15% between two polynomial pairs, compared to a sieving test. A new measure that better corresponds to sieving tests was designed. An article describing these new results is in preparation.

7.7. Mathematical Computation with SageMath

Participant: Paul Zimmermann.

Starting in March, Paul Zimmermann coordinated the English translation of the book “Calcul mathématique avec Sage”, and the update from version 5.9 to 8.0 of Sage. He also translated several chapters and proof-read the translation of all chapters. The current state of the English translation is available under a Creative Commons license (CC BY-SA) at https://members.loria.fr/PZimmermann/sagebook/english.html. A discussion is in process with an editor to publish a paper version.

7.8. Topics in Computational Number Theory Inspired by Peter L. Montgomery

Participants: Emmanuel Thomé, Paul Zimmermann.

Emmanuel Thomé and Paul Zimmermann contributed two chapters of the book “Topics in Computational Number Theory Inspired by Peter L. Montgomery”, coordinated by Arjen Lenstra and Joppe Bos, and published by Cambridge University Press. Together with Richard P. Brent and Alexander Kruppa, Paul Zimmermann wrote a chapter entitled “FFT extension for algebraic-group factorization algorithms” [12]. Emmanuel Thomé contributed a chapter entitled “The block Lanczos algorithm” [14].

7.9. Improved Methods for Finding Optimal Formulae for Bilinear Maps in a Finite Field

Participant: Svyatoslav Covanov.

In [17], we describe a method improving on the exhaustive search algorithm developed in [26]. We are able to compute new optimal formulae for the short product modulo X^5 and the circulant product modulo $(X^5 - 1)$. Moreover, we prove that there is essentially only one optimal decomposition of the product of 3×2 by 2×3 matrices up to the action of some group of automorphisms.

7.10. Big Prime Field FFT on the GPU

Participant: Svyatoslav Covanov.

In colloboration with L. Chen, D. Mohajerani and M. Moreno Maza, in [11], we compare various methods for the multiplication of polynomials, using the GPU. We compare the CRT method, using k machine-word primes, to the generalized Fermat prime method, for a prime of k machine-words, inspired by the work in [28]. For some degrees and k, we prove that the arithmetic operations with the generalized Fermat primes offer attractive performance both in terms of algebraic complexity and parallelism.

7.11. CM Plane Quartics

Participant: Hugo Labrande.

As a by-product of his PhD thesis defended in late 2016, Hugo Labrande contributed to a joint work with several authors, leading to an article [21] that provides examples of smooth plane quartics over $\mathbb{Q}$ with complex multiplication over $\overline{\mathbb{Q}}$ by a maximal order with primitive CM type. Several algorithms are used, in tight connection to the computation of Theta functions which was improved in Labrande's PhD thesis: reduction of period matrices, fast computation of Dixmier-Ohno invariants, and reconstruction from these invariants.

7.12. Explicit Isogenies in Genus 2 and 3

Participant: Enea Milio.

In [22], we present a quasi-linear algorithm to compute isogenies between Jacobians of curves of genus 2 and 3 starting from the equation of the curve and a maximal isotropic subgroup of the ℓ-torsion, for ℓ an odd prime number, generalizing Vélu's formula of genus 1. This work is based on the paper "Computing functions on Jacobians and their quotients" of Jean-Marc Couveignes and Tony Ezome. We improve their genus 2 case algorithm, generalize it for genus 3 hyperelliptic curves and introduce a way to deal with the genus 3 non-hyperelliptic case, using algebraic Theta functions.

7.13. Modular Polynomials of Hilbert Surfaces

Participant: Enea Milio.

In [23], together with Damien Robert from the LFANT team, we describe an evaluation/interpolation approach to compute modular polynomials on a Hilbert surface, which parametrizes abelian surfaces with maximal real multiplication. Under some heuristics we obtain a quasi-linear algorithm. The corresponding modular polynomials are much smaller than the ones on the Siegel threefold. We explain how to compute even smaller polynomials by using pullbacks of Theta functions to the Hilbert surface, and give an application to the CRT method to construct class polynomials.

7.14. Individual Logarithm Step in Non-prime Fields

Participant: Aurore Guillevic.

In [20], the previous work [33] on speeding-up the first phase of the individual discrete logarithm computation, the initial splitting, a.k.a. smoothing phase, is extended to any non-prime finite field $\mathbb{F}_{p^n}$ where n is composite. It is also applied to the new variant Tower-NFS.

7.15. Last Year Results that Appeared in 2017

Our work [6], in collaboration with J. Fried and N. Heninger from the University of Pennsylvania, describing a kilobit discrete logarithm computation for a trapdoored prime number has been published in Eurocrypt 2017.

A paper detailing the implementation of the ECM factoring algorithm on the Kalray MPPA-256 many-core processor, written as a collaboration between Jérémie Detrey and Pierrick Gaudry from CARAMBA, and Masahiro Ishii, Atsuo Inomata, and Kazutoshi Fujikawa from NAIST (Nara, Japan), was published in IEEE Transaction on Computers [2].

In [39], the notions of Square, saturation, integrals, multisets, bit patterns and tuples cryptanalysis are revised. A new Slice & Fuse paradigm to better exploit multiset type properties of block ciphers is proposed. With this refined analysis, we improve the best bounds proposed in such contexts against the following block ciphers: Threefish, Prince, Present and Rectangle.

In [3], we improve the existing impossible-differential attacks against Rijndael-160 and Rijndael-224.

Our work [10] about the computational power of the Measurement-based Quantum Computation model, written by Luc Sanselme and Simon Perdrix (from the CARTE team at LORIA), has appeared.

8. Bilateral Contracts and Grants with Industry

8.1. Training and Consulting with French Ministry of Defense

We have training and consulting activities with the French Ministry of Defense.

8.2. Consulting with Docapost

Together with the PESTO team, we have a contract with the Docapost company, the purpose of which is to impove their e-voting solution, adding some verifiability properties and switching to elliptic curve cryptography.

8.3. Consulting with Canton of Geneva

In this contract the goal is to audit and prove security properties of a new e-voting protocol to be used in a few cantons of Switzerland.

8.4. Research Contract with Orange

This contract with Orange Gardens at Chatillon-Montrouge is dedicated to the supervision of Sandra Rasoamiaramanana's PhD thesis about security in the white box context.

8.5. FUI Industrial Partnership on Lightweight Cryptography

This contract, called PACLIDO, is an FUI project with many companies dedicated to the definition of new lightweight cryptographic primitives for the IoT.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. PEPS CHARIoT

The PEPS CHARIoT ("CHiffrement Authentifié pour Renforcer l'IoT") project is dedicated to the study of authenticated encryption schemes, especially the CAESAR candidates, and to the performance analysis of those schemes on dedicated embedded architectures such as micro-controllers (MSP430, ARM and AVR). It involves Marine Minier (CARAMBA), Franck Rousseau (IMAG - Grenoble) and Pascal Lafourcade (LIMOS-UCA - Clermont-Ferrand).

9.2. International Research Visitors

9.2.1. Visits of International Scientists

Thorsten Kleinjung from EPFL visited the team from 6 to 10 February to work on the Number Field Sieve algorithm.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. Member of the Organizing Committees

- Together with Anne-Lise Charbonnier (Inria Nancy – Grand Est), the Caramba team organized 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).
- Emmanuel Thomé is a member of the steering committee of the conference series "Algorithmic Number Theory Symposium" (ANTS).
- Emmanuel Thomé is a member of the scientific directorate of the Dagstuhl computer science seminar series.

10.1.2.2. Member of the Conference Program Committees

- Jérémie Detrey was a member of the Program Committee of ECC 2017.
- Pierrick Gaudry was a member of the Program Committee of EUROCRYPT 2017.
- Aurore Guillevic was a member of the Program Commitee of PKC 2018, Latincrypt 2017 and JC2 2017.
- Marine Minier was a member of the Program Commitee of WCC 2017 and JC2 2017.
- Pierre-Jean Spaenlehauer was a member of the Program Commitee of ISSAC 2017.

10.1.3. Journal

10.1.3.1. Reviewer - Reviewing Activities

Members of the project-team did their share in reviewing submissions to renowned conferences and journals. Actual publications venues are not disclosed for anonymity reasons.

10.1.4. Invited Talks

- Jérémie Detrey was invited to give a talk at the Rencontres "Arithmétique de l'Informatique Mathématique" (RAIM 2017), Lyon, France.
- Aurore Guillevic was invited to give a talk at the Elliptic Curve Cryptography Conference (ECC17), Nijmegen, Netherlands.
- Emmanuel Thomé was invited to give a talk at the Elliptic Curve Cryptography Conference (ECC17), Nijmegen, Netherlands.
- Marine Minier was invited to give a talk at the Journées Nationales du pré-GDR Sécurité, Paris, France and at the CCA seminar, Paris, France.

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).
  - is a member of the *Comité Local Hygiène, Sécurité, et Conditions de Travail* of the Inria Nancy – Grand Est research center.
  - was a member of the hiring committee for the 2015 junior research positions (CR2) at Inria Bordeaux.
- 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*, of the “groupe de réflexion” *Calcul, Codage, Information* of the GDR-IM, of the advisory board of the OpenDreamKit european project, of the scientific council of the LIRMM laboratory in Montpellier, and chair of the organizing committee of the EJCIM (*École Jeunes Chercheurs Informatique Informatique Mathématique*) which will take place in Nancy in 2018.
- Marine Minier is
  - member of the CoS, poste MCF number 27MCF4376, Université de Rouen, November 2017.
  - member of the CoS, poste MCF number 27MCF575, Université de Grenoble Alpes, May 2017.
  - president of the CoS, poste MCF number 27MCF0955, Université de Lorraine, May 2017.
  - member of the CoS, poste MCF number 27MCF4191, Université de Lyon, May 2017.
  - member of the CoS, poste PR number 27PR0154, Université de Toulouse, May 2017.
  - in charge of the redaction for the LORIA of the Impact Project *Digital Trust*.

10.1.6. Research Administration

- Laurent Grémy was a member of the *Conseil de laboratoire* of the Loria.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Master: Marine Minier, *Sécurité des systèmes d’information*, 40h eq. TD, M2 Informatique, Université de Lorraine, Faculté des sciences et technologies, Vandœuvre-les-Nancy, France.

Master: Marine Minier, *Introduction à la cryptographie*, 18h eq. TD, M1 Informatique, Université de Lorraine, Faculté des sciences et technologies, Vandœuvre-les-Nancy, France.

Master: Marine Minier, *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*, 24 hours (lectures + exercises), 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.

Master: Pierre-Jean Spaenlehauer, *Initiation aux méthodes analytiques de la théorie des nombres, applications à la cryptographie*, 15h eq. TD, M2 Mathématiques MFA, Université de Lorraine, Faculté des sciences et technologies, Vandœuvre-les-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.

Master: Jérémie Detrey, *Introduction à la cryptographie*, 8 hours (lectures) + 10 hours (tutorial sessions) + 12 hours (practical sessions), Master Spécialisé, École des Mines de Nancy, France.

Licence: Marine Minier, *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*, 24 hours (practical sessions), L1, Université de Lorraine, Faculté des sciences et technologies, Vandœuvre-lès-Nancy, France.

2e année École Polytechnique, Aurore Guillevic, *Les bases de la programmation et de l'algorithmique*, (INF411), 32 hours (lab sessions), Palaiseau, France ("chargée d'enseignement").

10.2.2. Supervision

Internship: Léo Barré, *cube attacks and cube testers*, Université de Bordeaux, March–September (6 months), Pierre-Jean Spaenlehauer and Marine Minier.

Internship: Nicolas David, *Impact des racines réelles sur la sélection polynomiale pour le crible algébrique*, ENS Cachan, June–July (6 weeks), Paul Zimmermann.

Internship: Quentin Deschamps, *Étude de la sécurité du logarithme discret dans* $\mathrm{GF}(p^n)$ *lorsque* n *est composé*, ENS Lyon, July–August (6 weeks), Aurore Guillevic.

Internship: Joël Felderhoff, *infrastructures in complex cubic fields*, ENS-Lyon, June–July (6 weeks), Pierre-Jean Spaenlehauer.

Ph.D. in progress: Sandra Rasoamiaramanana, *Délivrance de contextes sécurisés par des approches hybrides*, since May 2017, Ph.D. CIFRE Orange Gardens, Marine Minier.

Ph.D. in progress: Paul Huynh, *analyse et conception de chiffrements authentifiés à bas coût*, since October 2017, Marine Minier.

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. defended [1]: Laurent Grémy, *Sieve algorithms for the discrete logarithm in medium characteristic finite fields*, defended on September 29th, 2017, Pierrick Gaudry & Marion Videau.

10.2.3. Juries

Marine Minier: president of the jury of the PhD: *Synchronisation et systèmes dynamiques : application à la cryptographie* defended by Brandon Dravie, July 2017, Université de Lorraine.

Marine Minier: president of the jury of the PhD: *Réseaux de capteurs et vie privée* defended by Jessye Dos Santos, August 2017, Université de Grenoble Alpes.

Marine Minier: president of the jury of the PhD: *Système de détection d'intrusion adapté au système de communication aéronautique ACARS* defended by Eric Asselin, June 2017, Université de Toulouse.

Marine Minier: president of the jury of the PhD: *Probabilistic models of partial enforcement in distributed systems* defended by Jordi Martori-Adrian, June 2017, Université de Lorraine.

Marine Minier: president of the jury of the PhD: *Méthodes de calculs sur les données chiffrées* defended by Marie Paindavoine, January 2017, Université de Lyon.

Emmanuel Thomé: reviewer of the PhD thesis: *Formules de Thomae pour les courbes algébriques résolubles* defended by Alexandre Le Meur, August 2017, Université de Rennes 1.

Paul Zimmermann: member of the jury of the PhD thesis: *Investigations in Computer-Aider Mathematics: Experimentation, Computation, and Certification* defended by Thomas Sibut-Pinote, December 2017, École polytechnique.

10.3. Popularization

- Pierrick Gaudry organized and participated in a debate fed by excerpts from movies on the topic of cryptography and privacy in March 2017. He also gave a podcast interview about electronic voting for Interstices [15].
- Pierre-Jean Spaenlehauer did a short presentation of asymetric cryptography to middle school students who were award winners of the Alkindi competition.
- Paul Zimmermann co-animated a “Math-en-Jeans” atelier with lycée Vauban in Luxembourg city (Luxembourg).

11. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] L. GRÉMY.*Sieve algorithms for the discrete logarithm in medium characteristic finite fields*, Université de Lorraine, September 2017, https://tel.archives-ouvertes.fr/tel-01647623.

Articles in International Peer-Reviewed Journal

[2] 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*, in "IEEE Transactions on Computers", December 2017, vol. 66, n^{o} 12, p. 2019-2030 [*DOI :* 10.1109/TC.2017.2704082], https://hal.inria.fr/hal-01299697.

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International Conferences with Proceedings

[5] M. ALAGGAN, M. CUNCHE, M. MINIER.*Non-interactive (t, n)-Incidence Counting from Differentially Private Indicator Vectors*, in "3rd International Workshop on Security and Privacy Analytics (IWSPA 2017)", Scottsdale, United States, March 2017, https://hal.inria.fr/hal-01485412.

[6] J. FRIED, P. GAUDRY, N. HENINGER, E. THOMÉ.*A kilobit hidden SNFS discrete logarithm computation*, in "36th Annual International Conference on the Theory and Applications of Cryptographic Techniques - Eurocrypt 2017", Paris, France, J.-S. CORON, J. B. NIELSEN (editors), Advances in Cryptology – EUROCRYPT 2017, Springer, April 2017, vol. 10210, https://arxiv.org/abs/1610.02874 [*DOI :* 10.1007/978-3-319-56620-7_8], https://hal.inria.fr/hal-01376934.

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[9] V. LEFÈVRE, P. ZIMMERMANN.*Optimized Binary64 and Binary128 Arithmetic with GNU MPFR*, in "24th IEEE Symposium on Computer Arithmetic (ARITH 24)", London, United Kingdom, July 2017, https://hal.inria.fr/hal-01502326.

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Conferences without Proceedings

[11] L. CHEN, S. COVANOV, D. MOHAJERANI, M. MORENO MAZA.*Big Prime Field FFT on the GPU*, in "ISSAC 2017", Kaiserslautern, Germany, July 2017, https://hal.archives-ouvertes.fr/hal-01518830.

Scientific Books (or Scientific Book chapters)

[12] R. P. BRENT, A. KRUPPA, P. ZIMMERMANN.*FFT extension for algebraic-group factorization algorithms*, in "Topics in Computational Number Theory Inspired by Peter L. Montgomery", J. W. BOS, A. K. LENSTRA (editors), Cambridge University Press, 2017, p. 189-205, https://hal.inria.fr/hal-01630907.

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Scientific Popularization

[15] P. GAUDRY, J. JONGWANE.*À propos du vote par Internet*, in "Interstices", March 2017, https://hal.inria.fr/hal-01533682.

Other Publications

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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

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Team CARTE

Creation of the Project-Team: 2009 January 01, updated into Team: 2016 January 01, end of the Team: 2017 December 31

Keywords:

Computer Science and Digital Science:

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A2.4.1. - Analysis
A4.5. - Formal methods for security
A7.2. - Logic in Computer Science
A8.6. - Information theory
A8.7. - Graph theory

Other Research Topics and Application Domains:

B9.4.1. - Computer science
B9.4.2. - Mathematics

1. Personnel

Research Scientists

Frédéric Dupuis [CNRS, Researcher, from Oct. 2017]
Nazim Fatès [Inria, Researcher]
Isabelle Gnaedig [Inria, Researcher]
Mathieu Hoyrup [Inria, Researcher]
Simon Perdrix [CNRS, Researcher]

Faculty Members

Emmanuel Jeandel [Team leader, Univ. de Lorraine, Professor, HDR]
Emmanuel Hainry [Univ. de Lorraine, Associate Professor]
Irène Marcovici [Univ. de Lorraine, Associate Professor (délégation Inria), from Sep 2017]
Romain Péchoux [Univ. de Lorraine, Associate Professor]

PhD Students

Pierre Mercuriali [Univ. de Lorraine]
Renaud Vilmart [Univ. de Lorraine]

Visiting Scientist

Ross Duncan [University of Strathclyde, Glasgow, Jun. 2017]

Administrative Assistants

Sophie Drouot [Inria]
Delphine Hubert [Univ. de Lorraine]
Martine Kuhlmann [CNRS]
Christelle Leveque [Univ. de Lorraine]

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 research activities of the CARTE team are now focused on the theme of Computation over Continuous Structures.

3. Research Program

3.1. Computer Virology

Historically, computer virology was one of the two main research directions of the team. This axis of research is no longer included the priorities of team as the members who were working on this topic have founded their own team.

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 [53], [79]; the Blum-Shub-Smale model (BSS), where the real numbers are treated as elementary entities [45]; the General Purpose Analog Computer (GPAC) introduced by Shannon [75]with continuous time.

3.3. Rewriting

The rewriting paradigm is widely used for specifying, modeling, 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 [46], MAUDE [49], and TOM [71].

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 [40], [52], [76].

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 [50]. 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 [77], [78]. 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 [41], [42].

4. Application Domains

4.1. 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., [39]), control theory (see e.g., [47]), neural networks (see e.g., [72]), and so on. We are interested in the formal decidability of properties of dynamical systems, such as reachability [63], the Skolem-Pisot problem [44], the computability of the ω-limit set [62]. 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 [75], on recursive analysis [79], on the algebraic approach [70] and on Markov computability [64]. 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. 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 modelling 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 [54], [55], [56], to weak termination [57], sufficient completeness [58] and probabilistic termination [60]. 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 [59], [61]. Provided program code can be translated into rule-based specifications, this approach can be applied to correctness proofs 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 [66], [67], [68]. 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

We worked on the computable aspects of an elementary problem in real analysis: extending a continuous function on a larger domain. More precisely, if a real-valued function f is defined on an interval $[0, a)$ (with $0 < a < 1$) and is computable there, under which conditions can it be extended to a computable function on $[0, 1]$? Our results show how the answer depends on a and on the way f converges at a. This provides new characterizations of already existing classes of real numbers previously defined in computability theory. Our work was presented at LICS 2017 [19].

6. New Software and Platforms

6.1. Software

6.1.1. FiatLux

FiatLux is a simulation program for cellular automata developed by Nazim Fatès. The project is currently available at the Inria GForge. It is under the CeCILL license.

7. New Results

7.1. Quantum Computing

Participants: Emmanuel Jeandel, Simon Perdrix, Renaud Vilmart.

- **ZX-calculus**

  The ZX-Calculus is a powerful graphical language for quantum mechanics and quantum information processing. The completeness of the language – i.e. the ability to derive any true equation – is a crucial question. In the quest for a complete ZX-calculus, supplementarity has been recently proved to be necessary for quantum diagram reasoning [73]. Roughly speaking, supplementarity consists in merging two subdiagrams when they are parameterized by antipodal angles. In [22], we introduce a generalised supplementarity – called cyclotomic supplementarity – which consists in merging n subdiagrams at once, when the n angles divide the circle into equal parts. We show that when n is an odd prime number, the cyclotomic supplementarity cannot be derived, leading to a countable family of new axioms for diagrammatic quantum reasoning. We exhibit another new simple axiom that cannot be derived from the existing rules of the ZX-Calculus, implying in particular the incompleteness of the language for the so-called Clifford+T quantum mechanics. We end up with a new axiomatisation of an extended ZX-Calculus, including an axiom schema for the cyclotomic supplementarity. This work has been presented at MFCS 2017 [22].

The ZX-Calculus is devoted to represent complex quantum evolutions. But the advantages of quantum computing still exist when working with rebits, and evolutions with real coefficients. Some models explicitly use rebits, but the ZX-Calculus cannot handle these evolutions as it is. Hence, in [21], we define an alternative language solely dealing with real matrices, with a new set of rules. We show that three of its non-trivial rules are not derivable from the other ones and we prove that the language is complete for the $\pi/2$-fragment. We define a generalisation of the Hadamard node, and exhibit two interpretations from and to the ZX-Calculus, showing the consistency between the two languages. This work has been presented at QPL 2017 [21].

- **Causality and Quantum Computing**

  Since the classic no-go theorems by [43] and [65], contextuality has gained great importance in the development of quantum information and computation. This key characteristic feature of quantum mechanics represents one of the most valuable resources at our disposal to break through the limits of classical computation and information processing, with various concrete application

  An important class of contextuality arguments in quantum foundations are the All-versus-Nothing (AvN) proofs, generalising a construction originally due to Mermin. In [11], we present a general formulation of All-versus-Nothing arguments, and a complete characterisation of all such arguments which arise from stabiliser states. We show that every AvN argument for an n-qubit stabiliser state can be reduced to an AvN proof for a three-qubit state which is local Clifford-equivalent to the tripartite GHZ state. This is achieved through a combinatorial characterisation of AvN arguments, the AvN triple Theorem, whose proof makes use of the theory of graph states. This result enables the development of a computational method to generate all the AvN arguments in Z2 on n-qubit stabiliser states. We also present new insights into the stabiliser formalism and its connections with logic. This work has been presented at QPL 2017 [25] and published in the Philosophical Transactions of the Royal Society A [11].

  Analyzing pseudo-telepathy graph games, we propose in [15] a way to build contextuality scenarios exhibiting the quantum supremacy using graph states. We consider the combinatorial structures generating equivalent scenarios. We investigate which scenarios are more multipartite and show that there exist graphs generating scenarios with a linear multipartiteness width. This work has been presented at FCT 2017 [15].

- **Measurement-based Quantum Computing**

  Measurement-based quantum computing (MBQC) is a universal model for quantum computation [74]. The combinatorial characterisation of determinism in this model [51], [48], [69], powered by measurements, and hence, fundamentally probabilistic, is the cornerstone of most of the breakthrough results in this 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 [48]. In [23], we show that the Pauli flow is necessary for real-MBQC, and not in general providing counterexamples for (complex) MBQC. We explore 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. Real MBQC has been used for interactive proofs 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 show that real bipartite MBQC is not universal proving that all measurements of real bipartite MBQC can be parallelised leading to constant depth computations. As a consequence, McKague techniques cannot lead to two-prover interactive proofs. This work has been presented at FCT 2017 [23].

7.2. Cellular automata as a model of computation

Participants: Nazim Fatès, Irène Marcovici.

The reversibility of classical cellular automata (CA) was examined for the case where the updates of the system are random. In this context, with B. Sethi and S. Das (India), we studied a particular form of reversibility: the possibility of returning infinitely often to the initial condition after a random number of time step,s this is the recurrence property of the system. We analysed this property for the simple rules and described the communication graph of the system [33].

We studied how to coordinate a team of agents to locate a hidden source on a two-dimensional discrete grid. The challenge 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 proposed to explain how agents may progressively approach the source by using only intermittent detections. With Q. Ladeveze, an intern, we re-examined in detail the properties of our bio-inspired algorithm that relies on the Reaction–Diffusion–Chemotaxis aggregation scheme to group agents that have limited abilities [38].

To study the robustness of asynchronous CA, we examined the coalescence phenomenon, which consists in observing the cases where two different initial conditions with the same sequence of updates quickly evolve to the same non-trivial configuration. With J. Francès de Mas, an intern, we studied the rules which always coalesce and those which exhibit a phase transition between a coalescing and non-coalescing behaviour. We proposed some formal explanations of non-trivial rapid coalescence giving lower bounds for the coalescence time of ECA 154 and ECA 62, and some first steps towards finding their upper bounds in order to prove that they have, respectively, quadratic and linear coalescence time [34].

We studied random mixtures of two deterministic Elementary Cellular Automata. There are 8088 such rules, called, diploid cellular automata. We used numerical simulations to perform some steps in the exploration of this space. As the mathematical analysis of such systems is a difficult task, we used numerical simulations to get insights into the dynamics of this class of stochastic cellular automata. We examined phase transitions and various types of symmetry breaking [17].

7.3. Extension of computable functions

Participant: Mathieu Hoyrup.

We worked on the computable aspects of an elementary problem in real analysis: extending a continuous function on a larger domain. More precisely, if a real-valued function f is defined on an interval $[0, a)$ (with $0 < a < 1$) and is computable there, under which conditions can it be extended to a computable function on $[0, 1]$? Although this question has a very simple formulation, it does not have a simple answer. We obtained many results showing how the answer depends on a and on the way f converges at a. Surprisingly, this problem provides new characterizations of already existing classes of real numbers previously defined in computability theory. This work is joint with Walid Gomaa and has been presented at LICS 2017 [19].

7.4. Genericity of weakly computable objects

Participant: Mathieu Hoyrup.

Computability theory abounds with classes of objects, defined for instance in terms of the computability content of the objects. A natural problem is then to compare these classes and separate them when possible. In order to separate two classes, one has to build an object that belongs to one class but not the other. So this object has to be computable in one sense but not the other. We show that in many cases these computability properties have a topological interpretation, and that the object to build must be at the same time computable in some weak topology (*weakly computable*) but *generic* in a stronger topology. We prove a general theorem stating the existence of such objects, thus providing a very handy tool to separate many classes. We use it in the study of the extension of computable functions (previous result) and in other situations. These results are presented in [13].

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Grants with Industry

- PRCE ANR SoftQPro has Atos-Bull as a partner.
- ITEA 3 Quantex involves several industrial partners: Siemens, KPN, Atos-Bull.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. ANR

- Simon Perdrix is PI of the PRCE ANR SoftQPro "Solutions logicielles pour l'optimisation des programmes et ressources quantiques". (2017- 2021) [Atos-Bull, LORIA, CEA, LRI].
- The team is partner of the ANR VanQuTe "Validation des technologies quantiques émergentes" (PRCI with Singapore) [LIP6, LORIA, SUTD, NUS, NTU] (2018-2022)
- The team is a 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.

9.2. European Initiatives

9.2.1. FP7 & H2020 Projects

Mathieu Hoyrup participates in the Marie-Curie RISE project Computing with Infinite Data coordinated by Dieter Spreen (Univ. Siegen) that has started in April 2017. We organized a workshop CCC'17 in Nancy in June 2017, that was also the first meeting of the project.

9.2.2. Collaborations in European Programs, Except FP7 & H2020

The team is partner of the ITEA3 Quantex project [LORIA, LRI, CEA/Leti, Atos-Bull, Siemens, TUDelft, KPN, EKUT] (2018-2020)

9.3. International Initiatives

Simon Perdrix is member of the STIC AmSud FoQCOSS with Argentina. He visited Quilmes University during 2 weeks in July 2017.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

Ross Duncan (Assistant Prof. at Strathclyde U., Glasgow), spent one month (June 2017) in our team as an invited professor at Université de Lorraine.

9.4.2. Internships

Jordina Francès de Mas, Quentin Ladeveze were interns in our team ; they worked on cellular automata and produced two technical reports (see [34] and [38]).

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

- Mathieu Hoyrup is member of the Steering Committee of the Conference Series *Computability in Europe* (CiE) for the period 2017-2021.

10.1.1.2. Member of the Organizing Committees

- Mathieu Hoyrup organized the workshop Continuity, Computability, Constructivity - From Logic to Algorithms (CCC) 2017, Nancy, June 2017.

10.1.2. Scientific Events Selection

10.1.2.1. Member of the Conference Program Committees

- Mathieu Hoyrup was co-chair of the workshop Continuity, Computability, Constructivity - From Logic to Algorithms (CCC) 2017, Nancy, June 2017.
- Emmanuel Jeandel was PC member of STACS 2017 (https://stacs2017.thi.uni-hannover.de/) and CIE 2017 (http://math.utu.fi/cie2017/).
- Romain Péchoux is PC member of the ETAPS affiliated workshop DICE 2018 (http://cl-informatik.uibk.ac.at/users/zini/events/dice18/).
- Simon Perdrix was PC member of QPL'17 (14th International Conference on Quantum Physics and Logic, 2017, Nijmegen, the Netherlands) ; IQFA'17 (Quantum Information: Foundations and Applications, 8th IQFA's Colloquium, 2017, Nice, France). He is PC member of the forthcoming MCU'18 (8th Conference on Machines, Computations and Universality) and DCM'18 (12th International Workshop on Developments in Computational Models, FLoC 2018, Oxford, UK).
- Nazim Fatès was a member of the PC of AUTOMATA 2017.

10.1.2.2. Reviewer

- Mathieu Hoyrup reviewed articles for CiE and LICS.
- Romain Péchoux reviewed articles for ISMVL and STACS.
- Simon Perdrix reviewed articles for LICS.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- Emmanuel Jeandel is member of the editorial board of RAIRO-ITA.
- Simon Perdrix is co-editor of the ERCIM issue on Quantum Computing.

10.1.3.2. Reviewer - Reviewing Activities

- Mathieu Hoyrup reviewed articles for Foundations of Computational Mathematics, Theory of Computing Systems, Mathematical Reviews.
- Romain Péchoux reviewed articles for Journal of Automated Reasoning and AMS Mathematical Reviews.
- Nazim Fatès served as a reviewer for *Natural computing* and *Theoretical computer science*.

10.1.4. Invited Talks

- Emmanuel Jeandel gave a course on Computability in Symbolic Dynamics on the Pingree Park Dynamics Workshop, http://web.cs.du.edu/~rpavlov/Pingree2017

- Emmanuel Jeandel gave a course on the Undecidability of the Domino Problem in the Winter School “Tiling Dynamical System” in Marseille, http://akiyama-arnoux.weebly.com/school.html
- Emmanuel Jeandel gave an invited talk on Higman-like theorems in symbolic dynamics at Logic Colloquium 2017, http://www.math-stockholm.se/konferenser-och-akti/logic-in-stockholm-2/logic-colloquium-201
- Romain Péchoux gave an invited talk on Higher order interpretations for higher order programs, cs department, Trinity College, Dublin.
- Simon Perdrix gave an invited talk on Measurement-based quantum computation at QPL’17 (14th International Conference on Quantum Physics and Logic, 2017).
- Simon Perdrix gave an invited talk on quantum algorithms at the event "l’Ordinateur Quantique" organised at IHP by the Fondation Sciences Mathématiques de Paris.

10.1.5. Leadership within the Scientific Community

Nazim Fatès is the vice-chair of the IFIP international working group 1.5 on Cellular automata and discrete dynamical systems.

Simon Perdrix is

- head of the GT IQ (groupe de Travail Informatique Quantique) @ GdR IM.
- board of GdR IQFA (Ingénierie Quantique, des aspects Fondamentaux aux Applications).

10.1.6. Scientific Expertise

Nazim Fatès was a project reviewer for the CONYCIT, the Chilean state agency for scientific research.

10.1.7. Research Administration

- Emmanuel Jeandel is the leader of the CARTE team.
- Isabelle Gnaedig is:
  - vice-leader of the CARTE team,
  - 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.
- Simon Perdrix is Scientific Secretary at CoNRS Section 6.

10.2. Teaching - Supervision - Juries

10.2.1. 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 Brabois, Université de Lorraine, France
  - 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, L2 Informatique
  - Formal Languages, 30h, L3 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

Master:

- 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 Jeandel:
  - Algorithmics and Complexity, 30h, M1 Informatique
- Romain Péchoux:
  - Mathematics for computer science, 30h, M1 SCA
  - Implicit Complexity, 15h, M2 Informatique
- Simon Perdrix:
  - Pépites Algorithmiques, 6h, M1/M2 at Ecole des Mines de Nancy.
- Nazim Fatès:
  - Systèmes complexes adapatatifs, M2, 10h, Informatique (UL)
  - Agents intelligents et collectifs M1, 15h, Sciences cognitives (UL)

10.2.2. Supervision

- Emmanuel Jeandel and Simon Perdrix supervised the Master Thesis of David Zonneveld on quantum circuits.
- Nazim Fatès and Irène Marcovici supervised the Erasmus Mundus master's thesis of Jordina Francès de Mas [34].
- 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).

10.2.3. Juries

- Emmanuel Jeandel reviewed the PhD thesis of Guilhem Gamard (Université Paul-Valery-Montpellier) and participated in the PhD defense of Laurent Grémy (Université de Lorraine), David Cattanéo (Université de Grenoble) and Sebastian Barbieri (ENS Lyon)
- Simon Perdrix participated in the PhD defense of Ruben Cohen (U. Paris Sud).

10.3. Popularization

- Nazim Fatès contributed to a booklet on the theme "Mathématiques et langages" edited by the Commission française pour l'enseignement des mathématiques (CFEM) for the forum "Mathématiques vivantes" (see http://forum-maths-vivantes.fr/-Panorama).
- This text appeared in a revised version on the CNRS website "images des mathématiques" [27].
- Nazim Fatès participated to a meeting ("projection-debat") at the Réseau et transport de l'électricité (RTE) at Villers-lès-Nancy on the these "Visages de la robotique", organised by "Sciences en lumière" (formerly Festival du film de chercheur).
- Nazim Fatès participated to a workshop on ethics in the "Forum des Sciences cognitives" organised by the "UFR mathématiques et informatique".
- Simon Perdrix gave an invited talk on quantum algorithms at the event "Mathématiques en mouvement sur l'Ordinateur quantique" organised by the Fondation Sciences Mathématiques de Paris at IHP.

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Major publications by the team in recent years

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Publications of the year

Articles in International Peer-Reviewed Journal

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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

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Creation of the Team: 2014 July 01, updated into Project-Team: 2015 July 01

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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.

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.

[0] See http://blog.programmableweb.com/2011/09/16/open-api-growth-a-visualization/

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 [19], 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 [18]. 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 [21] 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) [25] 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 [23] 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 [19]
- the algorithms based on commutative replicated data types (CRDT) [22].

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 [20] 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 [17].

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 [16].

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.

We extended some of our previous work around authorization policies for Enterprise Social Networks, and we propose two directions: a first one is dedicated to formal verification using PlusCal-2[11], while the other one is a formal approach for the Verification of AWS IAM Access Control Policies..

Recently, we started a work on service composition for software architects where services are coming from different providers with different plans (capacity, degree of resilience,...). The objective is to help the architects to select the most accurate services (wrt. to thier requirements, both functional and non functional) and plans for building their software. We also compute the properties that can be guarantee for the composition of these services.

4. New Software and Platforms

4.1. BeGoood

FUNCTIONAL DESCRIPTION: BeGoood is a generic system for managing non-regression tests on knowledge bases. BeGoood allows to define test plans in order to monitor the evolution of knowledge-bases. Any system answering queries by providing results in the form of set of strings can be tested with BeGoood. BeGoood has been developed following a REST architecture and is independent of any application domain. BeGoood is a part of the Kolflow infrastructure.

- Participant: Gérôme Canals
- Contact: Gérôme Canals
- URL: https://github.com/kolflow/begoood

4.2. MUTE

Multi-User Text Editor

FUNCTIONAL DESCRIPTION: MUTE (Multi-User Text Editor) is a web-based text editing tool that allows 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: Claudia-Lavinia Ignat, François Charoy, Gérald Oster and Luc André
- Contact: Gérald Oster
- URL: https://github.com/coast-team/mute-demo/

4.3. 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 events traces. These events traces can be produced randomly according to different parameters, can be extracted from real 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 term of execution time, memory footprint and merge result quality (compared to manual merge history stored in git repositories).

- Participants: Gérald Oster, Mehdi Ahmed-Nacer and Pascal Urso
- Contact: Pascal Urso
- URL: https://github.com/score-team/replication-benchmarker/

4.4. 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. Design and Analysis of Collaborative Editing Approaches

Participants: Matthieu Nicolas, Victorien Elvinger, Hoai Le Nguyen, Quentin Laporte Chabasse, Claudia-Lavinia Ignat [contact], Gérald Oster, François Charoy, Olivier Perrin.

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 amount of contributors and a high velocity of changes. This year we designed new optimistic replication algorithms for maintaining consistency for complex data such as wikis. We also designed a peer-to-peer web-based real-time collaborative editor relying on our proposed algorithms as well as a mechanism that balances awareness and disturbance in this kind of systems. We also started to study collaborative editing user behavior.

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 [2]. Our merging solution is based on an operational transformation approach for which we defined operations with high-level semantic 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.

Existing real-time collaborative editors rely on a central authority that stores user data which is a perceived privacy threat.We designed MUTE [8], a peer-to-peer web-based real-time collaborative editor that eliminates the disadvantages of central authority based systems. Users share their data with the collaborators they trust without having to store their data on a central place. MUTE features high scalability and supports offline and ad-hoc collaboration. MUTE relies on LogootSplit, a CRDT-based consistency maintenance algorithm for strings [15]. MUTE collaborative editor will be integrated in the virtual desktop of OpenPaaS::NG project [8].

When people work collaboratively on a shared document, they have two contradictory requirements on their editors that may affect the efficiency of their work. On the one hand, users would like to be aware of other users work on a particular part of the document. On the other hand, users would like to focus their attention on their own current work, with as little disturbance from the concurrent activities as possible. We designed a mechanism that lets users handle a balance between disturbance and awareness of concurrent updates [10]. Users can define focus regions and concentrate on the work in these regions without being disturbed by work of other users. Occasionally, users can preview concurrent updates and select a number of these updates to be integrated into the local copy.

We are interested in analysing user behavior during collaborative editing. This year we studied concurrency and conflicts in asynchronous collaboration [7]. We chose to study collaboration traces of distributed version control systems such as Git. We analysed Git repositories of four projects: Rails, IkiWiki, Samba and Linux Kernel. We analyzed the collaboration process of these projects at specific periods revealing how changes integration evolves during project development. We also analyzed how often users decide to rollback to previous document version when the integration process results in conflict. Finally, we studied the mechanism adopted by Git to consider changes made on two continuous lines as conflicting.

5.2. Trust-based Collaboration

Participants: Quang Vinh Dang, Claudia-Lavinia Ignat, Francois Charoy, Olivier Perrin, Mohammed Riyadh Abdmeziem, Hoang Long Nguyen.

Trust between users is an important factor for the success of a collaboration. Users might want to collaborate only with those users they trust. We are interested in assessing users trust according to their behaviour during collaboration in a large scale environment. 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 content of a document that has been written collaboratively. We investigated how to automatically assess the quality of Wikipedia articles in order to provide guidance for both authors and readers of Wikipedia. Most existing approaches for quality classification of Wikipedia articles rely on traditional machine learning with manual feature engineering, which requires a lot of expertise and effort and is language dependent. We proposed an approach that addresses the trade-off between accuracy, time complexity and language independence for the prediction models [5]. Our approach relying on Recurrent Neural Networks (RNN) eliminates disadvantages of feature engineering, i.e. it learns directly from raw data without human intervention and is language-neutral. Experimental results on English, French and Russian Wikipedia datasets show that our approach outperforms state-of-the-art solutions.

Rating prediction is a key task of e-commerce recommendation mechanisms. Recent studies in social recommendation enhance the performance of rating predictors by taking advantage of user relationships. However, these prediction approaches mostly rely on user personal information which is a privacy threat. We proposed dTrust [6], a simple social recommendation approach that avoids using user personal information. It relies uniquely on the topology of an anonymized trust-user-item network that combines user trust relations with user rating scores for items. This topology is fed into a deep feed-forward neural network. Experiments on real-world data sets showed that dTrust outperforms state-of-the-art in terms of Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) scores for both warm-start and cold-start problems.

One dimension of our work is dedicated to ensure consistency of the key server. We design Trusternity, which is a secure, scalable auditing mechanism using a blockchain to replace the gossiping mechanism of transparent log system. We have implemented Trusternity as a proof-of-concept, and we have led some evaluation about the detection of malicious behavior on the blockchain network.

Securing P2P collaborative system remains a critical issue for its widespread adoption. One of our goals is to ensure that communication between collaborating partner is secure from end to end. We need to encrypt exchange of operations among partners. For that we propose to rely on group keys management. One of the issue is that the composition of the partnership can change and this require to change the group key. Since we don't want a central server to manage keys, that would break the p2p nature of our approach we need to propose group key management protocols that are resilient to change in groups, even in group of large size. [3]

5.3. Cloud Provisioning for Elastic BPM

Participants: François Charoy, Samir Youcef, Guillaume Rosinosky.

Cloud computing provider do not help consumer to use optimally the available resources. For this, several approaches have been proposed [24] that take benefit from the elasticity of the Cloud, starting and stoppping virtual machines on demand. They suffer from several shortcomings. Often they consider only one objective, the reduction of the cost, or a level of quality of service. We proposed to optimize two conflicting objectives, the number of migrations of tenants that is helpful to reach the optimal cost and the cost incurred considering 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 [9].

5.4. Risk Management for the Deployment of a Business Process in a Multi-Cloud Context

Participants: Amina Ahmed-Nacer, Claude Godart, Samir Youcef.

The lack of trust in cloud organizations is often seen as braking forces 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) [4].
- Additionally are developing a simulation tool for supporting designer decision with the ability to balance risk with cost when selecting the best cloud configuration.

5.5. Scheduling and Resource Allocation in Business Processes

Participants: Khalid Benali, Abir Ismaili-Alaoui.

Business Process Management (BPM) is concerned with continuously enhancing business processes by adapting a systematic approach that enables companies to increase the performance of their existing business processes and achieve their business goals. Business processes are generaly considered as blind and stateless, which mean that in each business process execution results from past process instances are not taken into consideration.

The main objective of our current research is to exploit the data generated from previous instances in order to enhance business processes in regards with several aspects, such as improvement of process business logical correctness, optimization of business process modeling issues, or improvemment of resource allocation and scheduling procedure in order to particularly optimize costs and time (among other factors).

We focus currently on this last aspect, i.e. scheduling and resource allocation in business processes. Business Processes may contain automatic tasks and non automatic tasks, so managing resources depends on the type of those resources (human or machine) In this context, our work use machine learning techniques to analyze data generated from previous business process execution to improve business process scheduling. This step ensure the assignment of the most critical business process instance task to a qualified (and may be costly) human resource while minimizing global execution costs through assignement of “dummy” tasks to machine agents.

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.

7.1.2. Region Grand Est TV Paint (2017–2019)

Participants: Claudia-Lavinia Ignat [contact], Gérald Oster.

Partners: TVPaint Development, Inria COAST project-team

Website: https://www.tvpaint.com/

This is a follow-up project in collaboration with TVPaint Development financed by Region Grand Est.

The goal is to contribute to the creation of a collaborative system dedicated to manage the production of animated movies. This system has to manipulate a large amount of data in a safe and secure manner. Based on the previously proposed architecture and prototype, this project intends to design and implements a commercial product. In the framework of this project, we bring our expertise in data management, business process management, distributed systems and collaborative systems.

Coast funding : 81,600 €

7.2. National Initiatives

7.2.1. OpenPaas NG (2015–2019)

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.

7.3. International Initiatives

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

7.3.1.1. 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.

7.4. International Research Visitors

7.4.1. Visits of International Scientists

Valerie Shalin from Wright State University spent one month and a half (May-July 2017) in our team as part of the USCoast2 Inria associated team.

Weihai Yu from Arctic University of Norway spent two weeks in March 2017 in the team as invited professor.

7.4.2. Visits to International Teams

7.4.2.1. Research Stays Abroad

- Béatrice Linot spent 3 months at Wright State University as part of our collaboration with Dr Valerie Shalin and Prof. Amit Sheth, funded by her LUE PhD grant.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Events Organisation

8.1.1.1. Member of the Organizing Committees

- Claudia-Lavinia Ignat was member of 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 CDVE (International Conference on Cooperative Design, Visualization and Engineering) 2017 and The Fifteenth International Workshop on Collaborative Editing Systems in conjunction with CSCW 2017
- Olivier Perrin was PC Member of ICSOC 2017, CoopIS 2017, ATC 2017, MoLS 2017 and some workshops.
- François Charoy was PC Member of ICEBE (International Conference on Business Engineering) 2017, CTS 2017 (International Symposium on Collaborative Technologies and Systems), DG.O (International Conference on Digital Government Research) 2017, IEEE WETICE 2017, ICSOC 2017, IEEE International Conference on Business Information Systems, ISCRAM 2017 and of several workshops.
- Gérald Oster was a PC member of CoopIS (International Conference on Cooperative Information Systems) 2017, CSCW (21st ACM Conference on Computer-Supported Cooperative Work and Social Computing) 2018 (Online-first).
- Khalid Benali was PC Member of WorldCIST'17 (World Conference on Information Systems and Technologies), I3E 2017 (IFIP Conference on e-Business, e-Services and e-Society), ICICS 2017 (8th International Conference on Information and Communication Systems), INFORSID'2017, CloudTech'17 (Third International Conference of Cloud Computing Technologies and Applications), MEDES 2017 (9th International Conference on Management of Digital EcoSystems),

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

- Olivier Perrin reviewed papers for IEEE Transactions on Services Computing journal, IEEE Transactions on Parallel and Distributed Systems and Journal of Systems and Software.
- Claudia-Lavinia Ignat reviewed papers for Transactions on Parallel and Distributed Systems, Transactions on Internet Technology, Transactions on Interactive Intelligent Systems and CSCW 2018.
- Gérald Oster reviewed papers for Computer Supported Cooperative Work Journal and Concurrency and Computation: Practice and Experience journal.

8.1.4. Scientific Expertise

François Charoy was member of the HCERES committee for the CRI lab of Paris 1 Sorbonne

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.

- 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 was responsible for the “Security, Services, Systems and Network” track of the master degree in computer science at University of Lorraine from September 2013 to June 2017.

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 (in progress): Victorien Elvinger, Secured Replication for Peer-to-Peer Collaborative Infrastructures, started in 10/2015, François Charoy and Gérald Oster
- PhD (defended): Jordi Martori i Adrian, Data constraints for large-scale collaboration, started in 10/2013, defense in 5/2017, 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
- PhD (in progress): Anis Ahmed Nacer, Safe Service Composition, Olivier Perrin and François Charoy, started 3/2017
- PhD (in progress): Matthieu Nicolas, Optimisation of Replication Algorithms, Olivier Perrin and Gérald Oster, started 10/2017

8.2.3. Juries

- Claudia-Lavinia Ignat was member of CR recruitement jury at Inria Nancy-Grand Est

COAST members were members of the following PhD and HdR defense committees:

- Hala Skaf Molli, HdR, Université de Nantes, October 2017 (François Charoy)
- Mourad Bouneffa, HdR, Université du Littoral Côte d’Opale (Claude Godart)
- Elian Aubry, PhD, Université de Lorraine, December 2017 (François Charoy)
- Mohsen Sayed, PhD, Université de Lorraine, July 2017 (François Charoy)
- Fatma Slaimi, PhD, Université d’Aix Marseille (Claude Godart)
- Cheick Salmi, PhD, Ecole Nationale Supérieure de Mécanique et d’Aéronautique (Claude Godart)
- Emma Hachicha Belghith, PhD, Université Paris-Saclay (Claude Godart)
- Jihane Lakhrouit, PhD, ENSIAS Rabat (Claude Godart)
- Hafida Naim, PhD, Université d’Aix Marseille (Claude Godart)

8.3. Popularization

- In June 2017 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.

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 is member of Inria CAP Chercheurs commission. She is responsible with the activity kindergarten at AGOS Inria Nancy-Grand Est.

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Project-Team GAMBLE

Geometric Algorithms & Models Beyond the Linear & Euclidean realm

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

IN PARTNERSHIP WITH:
Université de Lorraine

RESEARCH CENTER
Nancy - Grand Est

THEME
Algorithmics, Computer Algebra and Cryptology

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Project-Team GAMBLE

Creation of the Team: 2017 January 01, updated into Project-Team: 2017 July 01

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Computer Science and Digital Science:

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A7.1. - Algorithms
A8.1. - Discrete mathematics, combinatorics
A8.3. - Geometry, Topology
A8.4. - Computer Algebra

Other Research Topics and Application Domains:

B1.1.1. - Structural biology
B1.2. - Neuroscience and cognitive science
B2.6. - Biological and medical imaging
B3. - Environment and planet
B5.2. - Design and manufacturing
B5.5. - Materials
B5.7. - 3D printing
B6.2.2. - Radio technology

1. Personnel

Research Scientists

Olivier Devillers [Team leader, Inria, Senior Researcher, HDR]
Sylvain Lazard [Inria, Senior Researcher, HDR]
Guillaume Moroz [Inria, Researcher]
Marc Pouget [Inria, Researcher]
Monique Teillaud [Inria, Senior Researcher, HDR]

Faculty Member

Laurent Dupont [Univ de Lorraine, Associate Professor]

Technical Staff

Eric Biagioli [Inria, until Mar 2017]

PhD Students

Sény Diatta [Univ de Lorraine, Mobility program until Sept 2017, then ATER from Oct 2017]
Charles Duménil [Univ de Lorraine]
Iordan Iordanov [Univ de Lorraine]
George Krait [Inria, CORDI-S, from Nov 2017]

Post-Doctoral Fellow

Vincent Despré [Inria, from Oct 2017]

Visiting Scientist

Gert Vegter [Univ of Groningen , from Sep 2017 until Oct 2017]

Administrative Assistants

Sophie Drouot [Inria]
Virginie Priester [CNRS]

2. Overall Objectives

2.1. Overall Objectives

Starting in the eighties, the emerging computational geometry community has put a lot of effort to design and analyze algorithms for geometric problems. The most commonly used framework was to study the worst-case theoretical complexity of geometric problems involving linear objects (points, lines, polyhedra...) in Euclidean spaces. This so-called *classical computational geometry* has some known limitations:

- Objects: dealing with objects only defined by linear equations.
- Ambient space: considering only Euclidean spaces.
- Complexity: worst-case complexities often do not capture realistic behaviour.
- Dimension: complexities are often exponential in the dimension.
- Robustness: ignoring degeneracies and rounding errors.

Even if these limitations have already got some attention from the community [26], a quick look at the flagship conference SoCG [0] proceedings shows that these topics still need a big effort.

It should be stressed that, in this document, the notion of certified algorithms is to be understood with respect to robustness issues. In other words, certification does not refer to programs that are proven correct with the help of mechnical proof assistants such as Coq, but to algorithms that are proven correct on paper even in the presence of degeneracies and computer-induced numerical rounding errors.

We address several of the above limitations:

• **Non-linear computational geometry.** Curved objects are ubiquitous in the world we live in. However, despite this ubiquity and decades of research in several communities, curved objects are far from being robustly and efficiently manipulated by geometric algorithms. Our work on, for instance, quadric intersections and certified drawing of plane curves has proven that dramatic improvements can be accomplished when the right mathematics and computer science are put into motion. In this direction, many problems are fundamental and solutions have potential industrial impact in Computer Aided Design and Robotics for instance. Intersecting NURBS (Non-uniform rational basis spline) and meshing singular surfaces in a certified manner are important examples of such problems.

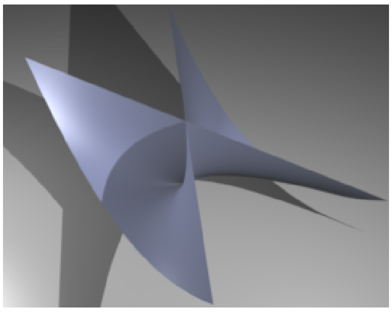
• **Non-Euclidean computational geometry.** Triangulations are central geometric data structures in many areas of science and engineering. Traditionally, their study has been limited to the Euclidean setting. Needs for triangulations in non-Euclidean settings have emerged in many areas dealing with objects whose sizes range from the nuclear to the astrophysical scale, and both in academia and in industry. It has become timely to extend the traditional focus on $\mathbb{R}^d$ of computational geometry and encompass non-Euclidean spaces.

• **Probability in computational geometry.** The design of efficient algorithms is driven by the analysis of their complexity. Traditionally, worst-case input and sometimes uniform distributions are considered and many results in these settings have had a great influence on the domain. Nowadays, it is necessary to be more subtle and to prove new results in between these two extreme settings. For instance, smoothed analysis, which was introduced for the simplex algorithm and which we applied successfully to convex hulls, proves that such promising alternatives exist.

3. Research Program

3.1. Non-linear computational geometry

[0] Symposium on Computational Geometry. http://www.computational-geometry.org/.



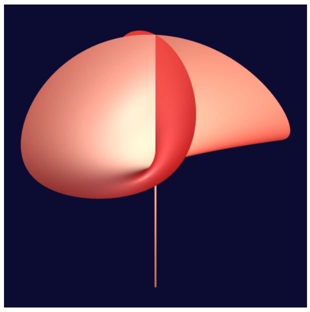


Figure 1. Two views of the Whitney umbrella (on the left, the "stick" of the umbrella, i.e., the negative z-axis, is missing). Right picture from [Wikipedia], left picture from [Lachaud et al.].

As mentioned above, curved objects are ubiquitous in real world problems modelings and in computer science and, despite this fact, there are very few problems on curved objects that admit robust and efficient algorithmic solutions without first discretizing the curved objects into meshes. Meshing curved objects induces some loss of accuracy which is sometimes not an issue but which can also be most problematic depending on the application. In addition, discretizing induces a combinatorial explosion which could cause a loss in efficiency compared to a direct solution on the curved objects (as our work on quadrics has demonstrated with flying colors [32], [33], [34], [36], [40]). But it is also crucial to know that even the process of computing meshes that approximate curved objects is far from being resolved. As a matter of fact there is no algorithm capable of computing in practice meshes with certified topology of even rather simple singular 3D surfaces, due to the high constants in the theoretical complexity and the difficulty of handling degenerate cases. Even in 2D, meshing an algebraic curve with the correct topology, that is in other words producing a correct drawing of the curve (without knowing where the domain of interest is), is a very difficult problem on which we have recently made important contributions [19], [20], [41].

It is thus to be understood that producing practical robust and efficient algorithmic solutions to geometric problems on curved objects is a challenge on all and even the most basic problems. The basicness and fundamentality of two problems we mentioned above on the intersection of 3D quadrics and on the drawing in a topologically certified way of plane algebraic curves show rather well that the domain is still at its infancy. And it should be stressed that these two sets of results were not anecdotical but flagship results produced during the lifetime of VEGAS team.

There are many problems in this theme that are expected to have high long-term impacts. Intersecting NURBS (Non-uniform rational basis spline) in a certified way is an important problem in computer-aided design and manufacturing. As hinted above, meshing objects in a certified way is important when topology matters. The 2D case, that is essentially drawing plane curves with the correct topology, is a fundamental problem with far-reaching applications in research or R&D. Notice that on such elementary problems it is often difficult to predict the reach of the applications; as an example, we were astonished by the scope of the applications of our software on 3D quadric intersection [0] which was used by researchers in, for instance, photochemistry, computer vision, statistics and mathematics.

3.2. Non-Euclidean computational geometry

Triangulations, in particular Delaunay triangulations, in the *Euclidean space*$\mathbb{R}^d$ have been extensively studied throughout the 20th century and they are still a very active research topic. Their mathematical properties are now well understood, many algorithms to construct them have been proposed and analyzed (see the book of

[0] QI: http://vegas.loria.fr/qi/.

Figure 2. Left: 3D mesh of a gyroid (triply periodic surface) [43]. Right: Simulation of a periodic Delaunay triangulation of the hyperbolic plane [15].

Aurenhammer *et al.* [14]). Some members of GAMBLE have been contributing to these algorithmic advances (see, e.g. [18], [51], [29], [17]); they have also contributed robust and efficient triangulation packages through the state-of-the-art Computational Geometry Algorithms Library CGAL, [0] whose impact extends far beyond computational geometry. Application fields include particle physics, fluid dynamics, shape matching, image processing, geometry processing, computer graphics, computer vision, shape reconstruction, mesh generation, virtual worlds, geophysics, and medical imaging. [0]

It is fair to say that little has been done on non-Euclidean spaces, in spite of the large number of questions raised by application domains. Needs for simulations or modeling in a variety of domains [0] ranging from the infinitely small (nuclear matter, nano-structures, biological data) to the infinitely large (astrophysics) have led us to consider 3D periodic Delaunay triangulations, which can be seen as Delaunay triangulations in the 3D *flat torus*, quotient of $\mathbb{R}^3$ under the action of some group of translations [24]. This work has already yielded a fruitful collaboration with astrophysicists [37], [52] and new collaborations with physicists are emerging. To the best of our knowledge, our CGAL package [23] is the only publicly available software that computes Delaunay triangulations of a 3D flat torus, in the special case where the domain is cubic. This case, although restrictive is already useful. [0] We have also generalized this algorithm to the case of general d-dimensional compact flat manifolds [25]. As far as non-compact manifolds are concerned, past approaches, limited to the two-dimensional case, have stayed theoretical [42].

Interestingly, even for the simple case of triangulations on the *sphere*, the software packages that are currently available are far from offering satisfactory solutions in terms of robustness and efficiency [22].

Moreover, while our solution for computing triangulations in hyperbolic spaces can be considered as ultimate [15], the case of *hyperbolic manifolds* has hardly been explored. Hyperbolic manifolds are quotients of a hyperbolic space by some group of hyperbolic isometries. Their triangulations can be seen as hyperbolic periodic triangulations. Periodic hyperbolic triangulations and meshes appear for instance in geometric modeling [44], neuromathematics [27], or physics [47]. Even the simplest possible case (a surface homeomorphic to the torus with two handles) shows strong mathematical difficulties [16], [49].

[0] http://www.cgal.org/
[0] See http://www.cgal.org/projects.html for details.
[0]

See http://www.loria.fr/~teillaud/PeriodicSpacesWorkshop/,
http://www.lorentzcenter.nl/lc/web/2009/357/info.php3?wsid=357 and
http://neg15.loria.fr/.
[0] See examples at http://www.cgal.org/projects.html

3.3. Probability in computational geometry

In most computational geometry papers, algorithms are analyzed in the worst-case setting. It often yields too pessimistic complexities that arise only in pathological situations that are unlikely to occur in practice. On the other hand, probabilistic geometry gives analyses of great precisions [45], [46], [21], but using hypotheses with much more randomness than in most realistic situations. We are developing new algorithmic designs improving state-of-the-art performances in random settings that are not overly simplified and that can thus reflect many realistic situations.

Twelve years ago, smooth analysis was introduced by Spielman and Teng analyzing the simplex algorithm by averaging on some noise on the data [50] (and they won the Gödel prize). In essence, this analysis smoothes the complexity around worst-case situations, thus avoiding pathological scenarios but without considering unrealistic randomness. In that sense, this method makes a bridge between full randomness and worst case situations by tuning the noise intensity. The analysis of computational geometry algorithms within this framework is still embryonic. To illustrate the difficulty of the problem, we started working in 2009 on the smooth analysis of the size of the convex hull of a point set, arguably the simplest computational geometry data structure; then, only one very rough result from 2004 existed [28] and we only obtained in 2015 breakthrough results, but still not definitive [31], [30], [35].

Another example of problem of different flavor concerns Delaunay triangulations, which are rather ubiquitous in computational geometry. When Delaunay triangulations are computed for reconstructing meshes from point clouds coming from 3D scanners, the worst-case scenario is, again, too pessimistic and the full randomness hypothesis is clearly not adapted. Some results exist for "good samplings of generic surfaces" [13] but the big result that everybody wishes for is an analysis for random samples (without the extra assumptions hidden in the "good" sampling) of possibly non-generic surfaces.

Trade-off between full randomness and worst case may also appear in other forms such as dependent distributions, or random distribution conditioned to be in some special configurations. Simulating these kinds of geometric distributions is currently out of reach for more than few hundred points [38] although it has practical applications in physics or networks.

4. Application Domains

4.1. Applications of computational geometry

Many domains of science can benefit from the results developed by GAMBLE. Curves and surfaces are ubiquitous in all sciences to understand and interpret raw data as well as experimental results. Still, the non-linear problems we address are rather basic and fundamental, and it is often difficult to predict the impact of solutions in that area. The short-term industrial impact is likely to be small because, on basic problems, industries have used ad hoc solutions for decades and have thus got used to it. The example of our work on quadric intersection is typical: even though we were fully convinced that intersecting 3D quadrics is such an elementary/fundamental problem that it ought to be useful, we were the first to be astonished by the scope of the applications of our software [0] (which was the first and still is the only one –to our knowledge– to compute robustly and efficiently the intersection of 3D quadrics) which has been used by researchers in, for instance, photochemistry, computer vision, statistics, and mathematics. Our work on certified drawing of plane (algebraic) curves falls in the same category. It seems obvious that it is widely useful to be able to draw curves correctly (recall also that part of the problem is to determine where to look in the plane) but it is quite hard to come up with specific examples of fields where this is relevant. A contrario, we know that certified meshing is critical in mechanical-design applications in robotics, which is a non-obvious application field. There, the singularities of a manipulator often have degrees higher than 10 and meshing the singular locus in a certified way is currently out of reach. As a result, researchers in robotics can only build physical prototypes for validating, or not, the approximate solutions given by non-certified numerical algorithms.

[0] QI: http://vegas.loria.fr/qi/.

The fact that several of our pieces of software for computing non-Euclidean triangulations have already been requested by users long before they become public is a good sign for their wide future impact once in CGAL. This will not come as a surprise, since most of the questions that we have been studying followed from discussions with researchers outside computer science and pure mathematics. Such researchers are either users of our algorithms and software, or we meet them in workshops. Let us only mention a few names here. We have already referred above to our collaboration with Rien van de Weijgaert [37], [52] (astrophysicist, Groningen, NL). Michael Schindler [48] (theoretical physicist, ENSPCI, CNRS, France) is using our prototype software for 3D periodic weighted triangulations. Stephen Hyde and Vanessa Robins (applied mathematics and physics at Australian National University) have recently signed a software license agreement with INRIA that allows their group to use our prototype for 3D periodic meshing. Olivier Faugeras (neuromathematics, Inria Sophia Antipolis) had come to us and mentioned his needs for good meshes of the Bolza surface [27] before we started to study them. Such contacts are very important both to get feedback about our research and to help us choose problems that are relevant for applications. These problems are at the same time challenging from the mathematical and algorithmic points of view. Note that our research and our software are generic, i.e., we are studying fundamental geometric questions, which do not depend on any specific application. This recipe has made the sucess of the CGAL library.

Probabilistic models for geometric data are widely used to model various situations ranging from cell phone distribution to quantum mechanics. The impact of our work on probabilistic distributions is twofold. On the one hand, our studies of properties of geometric objects built on such distributions will yield a better understanding of the above phenomena and has potential impact in many scientific domains. On the other hand, our work on simulations of probabilistic distributions will be used by other teams, more maths oriented, to study these distributions.

5. Highlights of the Year

5.1. Highlights of the Year

The project-team VEGAS terminated at the end of 2016. Our main highlight is actually the creation of the new project-team GAMBLE (Geometric Algorithms and Models Beyond the Linear and Euclidean realm) on July 1st.

Another highlight of this year is that after two failures, both ANR projects we are coordinating finally won at the ANR lottery with two projects that will start in 2018: ASPAG (ANR-17-CE40-0017) and SoS (ANR-17-CE40-0033).

6. New Software and Platforms

6.1. ISOTOP

Topology and geometry of planar algebraic curves
KEYWORDS: Topology - Curve plotting - Geometric computing
FUNCTIONAL DESCRIPTION: 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 has been developed since 2007 in collaboration with F. Rouillier from Inria Paris - Rocquencourt. It is based on the method described in [Cheng, J., Lazard, S., Pe

NEWS OF THE YEAR: In 2017, an ADT FastTrack funded a 6 months engineer contract to port the Maple code to C code. In addition, another local engineer from Inria Nancy (Benjamin Dexheimer) implemented a web server to improve the diffusion of our software.

- Participants: Elias Tsigaridas, Jinsan Cheng, Luis Penaranda, Marc Pouget and Sylvain Lazard
- Contact: Sylvain Lazard
- URL: http://vegas.loria.fr/isotop/

6.2. CGAL Package : 3D periodic regular triangulations

KEYWORDS: Flat torus - CGAL - Geometry - Geometric computing - Voronoi diagram - Delaunay triangulation - Triangulation

FUNCTIONAL DESCRIPTION: This class of CGAL (Computational Geometry Algorithms Library http://www.cgal.org) allows to build and handle periodic regular triangulations whose fundamental domain is a cube in 3D. Triangulations are built incrementally and can be modified by insertion of weighted points or removal of vertices. They offer location facilities for weighted points. The class offers nearest neighbor queries for the additively weighted distance and primitives to build the dual weighted Voronoi diagrams.

- Participants: Aymeric Pellé, Mael Rouxel-Labbe and Monique Teillaud
- Contact: Monique Teillaud
- URL: https://doc.cgal.org/latest/Manual/packages.html#PkgPeriodic3Triangulation3Summary

6.3. CGAL Package : 2D hyperbolic triangulations

KEYWORDS: Geometry - Delaunay triangulation - Hyperbolic space

FUNCTIONAL DESCRIPTION: This package implements the construction of Delaunay triangulations in the Poincaré disk model.

- Authors: Mikhail Bogdanov, Olivier Devillers and Monique Teillaud
- Contact: Monique Teillaud
- Publication: Hyperbolic Delaunay Complexes and Voronoi Diagrams Made Practical
- URL: https://github.com/CGAL/cgal-public-dev/tree/Hyperbolic_triangulation_2-MBogdanov

6.4. CGAL Package : 2D periodic hyperbolic triangulations

KEYWORDS: Geometry - Delaunay triangulation - Hyperbolic space

FUNCTIONAL DESCRIPTION: This module implements the computation of Delaunay triangulations of the Bolza surface.

- Authors: Iordan Iordanov and Monique Teillaud
- Contact: Monique Teillaud
- Publication: Implementing Delaunay Triangulations of the Bolza Surface
- URL: https://github.com/CGAL/cgal-public-dev/tree/Periodic_4_hyperbolic_triangulation_2-IIordanov

7. New Results

7.1. Non-Linear Computational Geometry

Participants: Sény Diatta, Laurent Dupont, George Krait, Sylvain Lazard, Guillaume Moroz, Marc Pouget.

7.1.1. *Reliable location with respect to the projection of a smooth space curve*

Consider a plane curve $\mathcal{B}$ defined as the projection of the intersection of two analytic surfaces in $\mathbb{R}^3$ or as the apparent contour of a surface. In general, $\mathcal{B}$ has node or cusp singular points and thus is a singular curve. Our main contribution [9] is the computation of a data structure for answering point location queries with respect to the subdivision of the plane induced by $\mathcal{B}$. This data structure is composed of an approximation of the space curve together with a topological representation of its projection $\mathcal{B}$. Since $\mathcal{B}$ is a singular curve, it is challenging to design a method only based on reliable numerical algorithms.

In a previous work [39], we have shown how to describe the set of singularities of $\mathcal{B}$ as regular solutions of a so-called ball system suitable for a numerical subdivision solver. Here, 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 $\mathcal{B}$ is encoded as an extended planar combinatorial map allowing point location. We experimented our method and show that our reliable numerical approach can handle classes of examples that are not reachable by symbolic methods.

7.1.2. *Computing effectively stabilizing controllers for a class of nD systems*

In this paper [1], we study the internal stabilizability and internal stabilization problems for multidimensional (nD) systems. Within the fractional representation approach, a multidimensional system can be studied by means of matrices with entries in the integral domain of structurally stable rational fractions, namely the ring of rational functions which have no poles in the closed unit polydisc $\overline{\mathbb{U}}^n = \{z = (z_1, ..., z_n) \in \mathbb{C}^n \mid |z_1| \leq 1, ..., |z_n| \leq 1\}$.

It is known that the internal stabilizability of a multidimensional system can be investigated by studying a certain polynomial ideal $I = \langle p_1, ..., p_r \rangle$ that can be explicitly described in terms of the transfer matrix of the plant. More precisely the system is stabilizable if and only if $V(I) = \{z \in \mathbb{C}^n \mid p_1(z) = \cdots = p_r(z) = 0\} \cap \overline{\mathbb{U}}^n = \varnothing$. In the present article, we consider the specific class of linear nD systems (which includes the class of 2D systems) for which the ideal I is zero-dimensional, i.e., the p_i's have only a finite number of common complex zeros. We propose effective symbolic-numeric algorithms for testing if $V(I) \cap \overline{\mathbb{U}}^n = \varnothing$, as well as for computing, if it exists, a stable polynomial $p \in I$ which allows the effective computation of a stabilizing controller. We illustrate our algorithms through an example and finally provide running times of prototype implementations for 2D and 3D systems.

7.2. Non-Euclidean Computational Geometry

Participants: Vincent Despré, Iordan Iordanov, Monique Teillaud.

7.2.1. *Implementing Delaunay Triangulations of the Bolza Surface*

The CGAL library offers software packages to compute Delaunay triangulations of the (flat) torus of genus one in two and three dimensions. To the best of our knowledge, there is no available software for the simplest possible extension, i.e., the Bolza surface, a hyperbolic manifold homeomorphic to a torus of genus two. We present an implementation based on the theoretical results and the incremental algorithm proposed recently. We describe the representation of the triangulation, we detail the different steps of the algorithm, we study predicates, and report experimental results [5]. The implementation is publicly available in the development branch of CGAL on `github`[0] and will soon be submitted for integration in the library.

[0] https://members.loria.fr/Monique.Teillaud/DT_Bolza_SoCG17/

7.3. Probabilistic Analysis of Geometric Data Structures and Algorithms

Participants: Olivier Devillers, Charles Duménil.

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

A good sample is a point set such that any ball of radius ϵ contains a constant number of points. The Delaunay triangulation of a good sample is proved to have linear size, unfortunately this is not enough to ensure a good time complexity of the randomized incremental construction of the Delaunay triangulation. In this paper we prove that a random Bernoulli sample of a good sample has a triangulation of linear size. This result allows to prove that the randomized incremental construction needs an expected linear size and an expected $O(n \log n)$ time [8].

This work was done in collaboration with Marc Glisse (Project-team DATASHAPE).

7.3.2. Delaunay triangulation of a random sampling of a generic surface

The complexity of the Delaunay triangulation of n points distributed on a surface ranges from linear to quadratic. We prove that when the points are evenly distributed on a smooth compact generic surface the expected size of the Delaunay triangulation is $O(n)$. This result has to be compared with a bound of $O(n \log n)$ when the points are a deterministic good sample of the surface under the same hypotheses on the surface [13].

7.4. Classical Computational Geometry and Graph Drawing

Participants: Olivier Devillers, Sylvain Lazard.

7.4.1. Celestial Walk: A Terminating Oblivious Walk for Convex Subdivisions

We present a new oblivious walking strategy for convex subdivisions. Our walk is faster than the straight walk and more generally applicable than the visiblity walk. To prove termination of our walk we use a novel monotonically decreasing distance measure [10].

This work was done in collaboration with Wouter Kuijper and Victor Ermolaev (Nedap Security Management).

7.4.2. Snap rounding polyhedral subdivisions

Let $\mathcal{P}$ be a set of n polygons in $\mathbb{R}^3$, each of constant complexity and with pairwise disjoint interiors. We propose a rounding algorithm that maps $\mathcal{P}$ to a simplicial complex $\mathcal{Q}$ whose vertices have integer coordinates. Every face of $\mathcal{P}$ is mapped to a set of faces (or edges or vertices) of $\mathcal{Q}$ and the mapping from $\mathcal{P}$ to $\mathcal{Q}$ can be build through a continuous motion of the faces such that (i) the L_∞ Hausdorff distance between a face and its image during the motion is at most 3/2 and (ii) if two points become equal during the motion they remain equal through the rest of the motion. In the worse, the size of $\mathcal{Q}$ is $O(n^{15})$, but, under reasonable hypotheses, this complexities decreases to $O(n^5)$.

This work was done in collaboration with William J. Lenhart (Williams College, USA).

7.4.3. Explicit array-based compact data structures for triangulations

We consider the problem of designing space efficient solutions for representing triangle meshes. Our main result is a new explicit data structure for compactly representing planar triangulations: if one is allowed to permute input vertices, then a triangulation with n vertices requires at most $4n$ references ($5n$ references if vertex permutations are not allowed). Our solution combines existing techniques from mesh encoding with a novel use of maximal Schnyder woods. Our approach extends to higher genus triangulations and could be applied to other families of meshes (such as quadrangular or polygonal meshes). As far as we know, our solution provides the most parsimonious data structures for triangulations, allowing constant time navigation. Our data structures require linear construction time, and are fast decodable from a standard compressed format without using additional memory allocation. All bounds, concerning storage requirements and navigation performances, hold in the worst case. We have implemented and tested our results, and experiments confirm the practical interest of compact data structures.

This work was done in collaboration with Luca Castelli Aleardi (LIX).

8. Bilateral Contracts and Grants with Industry

8.1. 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.

9. Partnerships and Cooperations

9.1. Regional Initiatives

We organized, with colleagues of the mathematics department (Institut Elie Cartan Nancy) a regular working group about geometry and probability.

9.2. National Initiatives

9.2.1. 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.

The project has a total budget of 100kE. It started on March 1st 2014 and will finished in August 2018. It is coordinated by Guillaume Moroz, with a participation of 60%, and Marc Pouget with a participation of 40%.

Project website: https://project.inria.fr/singcast/.

9.3. International Initiatives

9.3.1. Inria Associate Teams Not Involved in an Inria International Lab

9.3.1.1. Astonishing

Title: ASsociate Team On Non-ISH euclIdeaN Geometry

International Partners (Institution - Laboratory - Researcher):

University of Groningen (Netherlands) - Johann Bernouilli Institute of Mathematics and Computer Science - Gert Vegter

University of Luxembourg - Mathematics Research Unit - Jean-Marc Schlenker

Université Paris Est Marne-la-Vallée - Laboratoire d'Informatique Gaspard Monge - Éric Colin de Verdière

Start year: 2017

See also: https://members.loria.fr/Monique.Teillaud/collab/Astonishing/

Some research directions in computational geometry have hardly been explored. The spaces in which most algorithms have been designed are the Euclidean spaces R^d. To extend further the scope of applicability of computational geometry, other spaces must be considered, as shown by the concrete needs expressed by our contacts in various fields as well as in the literature. Delaunay triangulations in non-Euclidean spaces are required, e.g., in geometric modeling, neuromathematics, or physics. Topological problems for curves and graphs on surfaces arise in various applications in computer graphics and road map design. Providing robust implementations of these results is a key towards their reusability in more applied fields. We aim at studying various structures and algorithms in other spaces than R^d, 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.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

Gert Vegter spent three weeks in GAMBLE in the framework of the Astonishing associate team.

9.4.2. Visits to International Teams

Olivier Devillers spent one month at Computational Geometry Lab of Carleton University http://cglab.ca/about.html.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. Member of the Organizing Committees

Sylvain Lazard organized with S. Whitesides (Victoria University) the 16th Workshop on Computational Geometry at the Bellairs Research Institute of McGill University in Feb. (1 week workshop on invitation).

Monique Teillaud co-organized with Claire Mathieu Celebrating Claude Puech's birthday, Paris, June 12.

Monique Teillaud co-organized the workshop Geometric Aspects of Materials Science with Vanessa Robins and Ileana Streinu, Brisbane, Australia, July 4–5.

Monique Teillaud co-organized with the Astonishing partners the Astonishing workshop at Loria/Inria nancy, September 25–26.

10.1.2. Scientific Events Selection

10.1.2.1. Member of the Conference Program Committees

Sylvain Lazard was a member of the program committee of SoCG, *Symposium on Computational Geometry*.

Monique Teillaud was a member of the program committee of WADS, *Algorithms and Data Structures Symposium*.

10.1.2.2. 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.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

Monique Teillaud is a managing editor of JoCG, *Journal of Computational Geometry* and a member of the editorial board of IJCGA, *International Journal of Computational Geometry and Applications*.

Marc Pouget and Monique Teillaud are members of the CGAL editorial board.

10.1.3.2. 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.

10.1.4. Invited Talks

Monique Teillaud was an invited speaker of CATS, *Computational & Algorithmic Topology*, Sydney, Australia, June 27 – July 1st.

Guillaume Moroz was invited to give a talk at the Effective Geometry and Algebra seminar at IRMAR.

10.1.5. Leadership within the Scientific Community

10.1.5.1. Steering Committees

Monique Teillaud is chairing the Steering Committee of the Symposium on Computational Geometry (SoCG). She was a member of the Steering Committee of the European Symposium on Algorithms (ESA) until September.

10.1.5.2. Learned societies

Monique Teillaud is a member of the Scientific Board of the *Société Informatique de France* (SIF).

10.1.6. Scientific Expertise

Monique Teillaud acted as a reviewer for the DFG, *Deutsche Forschungsgemeinschaft* (German Research Foundation).

10.1.7. Research Administration

10.1.7.1. Hiring committees

Olivier Devillers was the representative of LORIA in the hiring committee for an Associate Professor (MCF) position (IUT St Dié/LORIA) and composed the committee with the president.

10.1.7.2. National committees

L. Dupont is the secretary of *Commission Pédagogique Nationale Carrières Sociales / Information-Communication / Métiers du Multimédia et de l'Internet* (since May).

M. Teillaud is a member of the working group for the BIL, *Base d'Information des Logiciels* of Inria.

10.1.7.3. Local Committees and Responsabilities

O. Devillers: Elected member to *Pole AM2I* the council that gathers labs in mathematics, computer science, and control theory at *Université de Lorraine*.

L. Dupont Instigator (June 2016) and head of the Bachelor diploma *Licence Professionnele Animation des Communautés et Réseaux Socionumériques*, Université de Lorraine.

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.

10.1.7.4. 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.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Master: Olivier Devillers, *Synthèse, image et géométrie*, 12h (academic year 2017-18), IPAC-R, Université de Lorraine. https://members.loria.fr/Olivier.Devillers/master/

Master: Olivier Devillers and Monique Teillaud, *Computational Geometry*, 24h (academic year 2017-18), Master2 Informatique, ENS Lyon https://members.loria.fr/Monique.Teillaud/Master2-ENS-Lyon/.

Licence: Sény Diatta, *Algorithme et Programmation*, 54h, L1, Université de Lorraine, France.

Licence: Sény Diatta, *Outils Informatiques et Internet*, 42h, L1, Université de Lorraine, France.

Licence: Charles Duménil, *Mathématiques*, 42h, L2, Université de Lorraine, France.

Licence: Charles Duménil, *Logiciel*, 20h, L2, Université de Lorraine, France.

Licence: Charles Duménil, *Algorithmique et programmation avancée*, 34h, M2, 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 *Databases* 30h L3, Université de Lorraine, France,

Licence: Laurent Dupont *Web devloppment and Social networks* 80h L3, Université de Lorraine, France.

Licence: Iordan Iordanov, *Algorithmique et Programmation*, 64h, L1, Université de Lorraine, France.

Licence: Iordan Iordanov, *Systèmes de gestion de bases de données*, 20h, L2, Université de Lorraine, France.

Licence: Iordan Iordanov, *Algorithmique et développement web*, 28h, L2, Université de Lorraine, France.

Licence: Iordan Iordanov, *Programmation objet et événementielle*, 16h, L3, Université de Lorraine, France.

Licence: Sylvain Lazard, *Algorithms and Complexity*, 25h, L3, Université de Lorraine, France.

Master: Marc Pouget, *Introduction to computational geometry*, 10.5h, M2, École Nationale Supérieure de Géologie, France.

10.2.2. Supervision

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.

PhD in progress: George Krait, Topology of singular curves and surfaces, applications to visualization and robotics, started in Nov. 2017, supervised by Sylvain Lazard, Guillaume Moroz and Marc Pouget.

Postdoc: Vincent Despré, Triangulating surfaces with complex projective structures, started in Nov. 2017, supervised by Monique Teillaud.

10.2.3. Internships

Jian Qian, from Ècole Normale Supérieure Paris, did a L3 internship from Jul 2017 until Aug 2017 co-advised by Guillaume Moroz and Marc Pouget on a topic of ANR SingCAST.

Guillermo Alfonso Reyes Guzman, from Université de Lorraine, did a Master internship from March 2017 until July 2017 advised by O. Devillers on deletion in 3D Delaunay triangulation.

Camille Truong-Allie (Master 1, "research path", École des Mines de Nancy), Lloyd algorithm in the flat torus, started in October, supervised by Monique Teillaud.

10.3. Popularization

L. Dupont participated to several days of popularization of computerscience: Open Bidouille Camp March, 26th 2017, popularization of programming, general audience ; ISN day March, 30th 2017, popularization of computerscience for high-school teachers ; Fête de la Science 14th October 2017 Inria event, general audience, and Google Day in Nancy 21st October 2017, general audience.

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Project-Team LARSEN

Lifelong Autonomy and interaction skills for Robots in a Sensing ENvironment

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
Robotics and Smart environments

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Project-Team LARSEN

Creation of the Team: 2015 January 01, updated into Project-Team: 2017 December 01

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Computer Science and Digital Science:

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B2.5.3. - Assistance for elderly
B5.1. - Factory of the future
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B7.2.1. - Smart vehicles

1. Personnel

Research Scientists

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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 [44], [56]. 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 [44], [53].

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 [51].

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 [43] 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 [64], [53]. However, current reinforcement learning algorithms require hundreds of trials/episodes to learn a single, often simplified, task [53], 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 [54], [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 [50]. 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 [61], [50], [42]).

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 [67]. Most Human-Robot Interaction (HRI) studies focus on verbal communication [63] 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 [65] and robotic co-workers [59]. 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 [47].

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) [66] 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 [49], 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 [48]. 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 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.

[0] See the Robotics 2020 Multi-Annual Roadmap [57].
[0] OHS (*Office d'Hygiène Sociale*) is an association managing several rehabilitation or retirement home structures.
[0] See the Robotics 2020 Multi-Annual Roadmap [57], section 2.5.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Awards

- "2017 ISAL Award for Distinguished Young Investigator in the field of Artificial Life" to Jean-Baptiste Mouret
- "Prix du stage de recherche" awarded by the École Polytechnique to Rémi Pautrat (intern, supervised by Jean-Baptiste Mouret)
- "Prix de thèse DGA" awarded to Antoine Cully (former PhD student, co-supervised by Jean-Baptiste Mouret)

5.1.2. New Projects

- beginning of the AnDy project (H2020)
- beginning of the collaboration with ScanPyramds about "Minimally invasive robotics for heritage buildings"
- beginning of a new collaboration with Diatelic, a subsidiary of the Pharmagest group, for the development of an innovative tele-assistance service based on smart home technologies in order to allow elderlies to stay in their home longer. A PhD thesis has been funded by Diatelic to support this collaboration.

BEST PAPERS AWARDS :

[27] **Genetic and Evolutionary Computation Conference (GECCO 2017)**. A. GAIER, A. ASTEROTH, J.-B. MOURET.

[26] **18th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference**. A. GAIER, A. ASTEROTH, J.-B. MOURET.

6. New Software and Platforms

6.1. ProMP_iCub

iCub Learning Trajectories with ProMP

KEYWORDS: Gaussian processes - Robotics

FUNCTIONAL DESCRIPTION: A set of matlab modules to learn, replay and infer the continuation of trajectories in robotics using Probabilistic Movement Primitives (ProMP).

- Contact: Serena Ivaldi
- Publication: Prediction of Intention during Interaction with iCub with Probabilistic Movement Primitives
- URL: https://github.com/inria-larsen/icubLearningTrajectories

6.2. Limbo

LIbrary for Model-based Bayesian Optimization

KEYWORDS: Black-box optimization - C++ - Global optimization - Machine learning - Policy Learning - Bayesian optimization - Gaussian processes

FUNCTIONAL DESCRIPTION: Limbo is an open-source C++11 library for Gaussian processes and 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.

NEWS OF THE YEAR: Release 2.0 (2017) with: - serialization of Gaussian process models - new architecture for kernel and mean functions - automatic and extensive benchmarks for Gaussian processes regression and Bayesian optimization (generated weekly) - better random generator (thread-safe, c++11) - generation of the documentation for each release

- Partners: UPMC - Imperial College London
- Contact: Jean-Baptiste Mouret
- URL: http://www.resibots.eu/limbo

6.3. xsens_driver

KEYWORD: IMU 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 your device, you can use the mtdevice.py script (or the vendor tool on Windows).

RELEASE FUNCTIONAL DESCRIPTION: Support of fourth generation of devices. Support of ubuntu 16.04. Support of ROS Jade and ROS Kinetic.
NEWS OF THE YEAR: version 2.1.0 (2017-04-14) - several bugfixes and a new option.

- Contact: Francis Colas
- URL: https://github.com/ethz-asl/ethzasl_xsens_driver

6.4. 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/

6.5. libdynamixel

KEYWORD: Robotics
FUNCTIONAL DESCRIPTION: The libdynamixel is a high-performance C++11 interface to the Dynamixel actuators (including the Dynamixel Pro range). It provides a high-level interface (designed to be easy to sue), a low-level interface (designed to add no overhead on top of the protocol), and a command-line tool for scripting and maintenance operations. The main emphasis is on performance and compatibility with modern C++.

- Contact: Jean-Baptiste Mouret
- URL: http://github.com/resibots/libdynamixel

7. New Results

7.1. Lifelong Autonomy

7.1.1. Sensorized environment

7.1.1.1. Localisation of Robots on a 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 Aurelien Andre (master student from Univ. Lorraine), we have focused on tracking robots on several scenarios based on data originated from the sensing tiles and collected the previous years. We have proposed a new approach to build relevant clusters of tiles (based on connexity). For single robot scenarios, we have focused on basic algorithms (for instance, Kalman filter) and on Probability Data Association Filter to consider the possibility of false positive in the bayesian filter. Then, for multi-target tracking, we have investigated elaborate strategies to associate atomic measures to the tracked targets like JPDAF (Joint Probability Data Association Filter algorithm [58]) and JPDAMF (Joint Probability Data Association Merged Filter [45]) in order to consider measures resulting from several targets.

7.1.1.2. High Integrity Personal Tracking Using Fault Tolerant Multi-Sensor Data Fusion

Participants: François Charpillet, Maan Badaoui El-Najjar.

Maan Badaoui El Najjar is professor at university of Lille and he is the head of the DiCOT Team "Diagnostic, Control and Observation for fault Tolerant Systems" of the CRIStAL Laboratory.

The objective of this PhD work is to study the possibilities offered by the above mentioned load-sensing floor. The idea is to combine the information from each sensor (load sensors and accelerometers) to identify daily living activities (walking, standing, lying down, sitting, falling) and to create a positioning system for the person in the apartment. The approach is based on information theory to address the detection of outliers during the fusion process. This is based on informational filters and fault detection to identify and eliminate faulty measurements. This work was carried through the PhD Thesis of Mohamad Daher under the supervision of François Charpillet and Maan Badaoui El Najjar. This thesis was defended at university of Lille on the 13th December 2017.

Publication: [14]

7.1.1.3. Active Sensing and Multi-Camera Tracking

Participants: 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. 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 [43] by tracking several persons with fixed camera based on particle filters and Simultaneous Tracking and Activity Recognition approach [49].

This year, approaches based on Monte-Carlo Tree Search algorithms (MCTS) like POMCP [60] have been used to build policies for following a single person with several controllable cameras in a simulated environment.

7.1.2. Partially Observable Markovian Decision Processes (POMDP)

7.1.2.1. Solving ρ-POMDP using Lipschitz Properties

Participant: Vincent Thomas.

We are currently investigating how to solve continuous MDP and ρ-POMDP by using Lipschitz property (rather than classical Piecewise Linear and Convex property used to solve POMDP). We have proven that if the transition and reward functions are lipschtiz-continuous, the value function has the same property.

With Mathieu Fehr (Ulm ENS student), we have studied new algorithm based on HSVI (Heuristic Search Value Iteration [62]) to take advantage of the lipschitz continuity property. The properties of these algorithms are currently investigated.

7.1.3. Distributed Exploration of an Unknown Environment by a Swarm of Robots

Participants: Nassim Kalde, François Charpillet, Olivier Simonin.

Olivier Simonin is Professeur at INSA Lyon and is the scientific leader of Chroma Team.

In this PhD, we have explored the issue for a team of cooperating mobile robots to intelligently explore an unknown environment. This question has been addressed both in the framework of sequential decision making and frontier based exploration. Considered environments includes static or populated environments.

This work was carried through the PhD Thesis of Nassim Fates under the supervision of François Charpillet and Olivier Simonin. This thesis was defended on the 12th December 2017.

7.1.4. Robot Learning

7.1.4.1. Black-box Data-efficient RObot Policy Search (Black-DROPS)

Participants: Konstantinos Chatzilygeroudis, Dorian Goepp, Rituraj Kaushik, Jean-Baptiste Mouret.

The most data-efficient algorithms for reinforcement learning (RL) in robotics are based on uncertain dynamical models: after each episode, they first learn a dynamical model of the robot, then they use an optimization algorithm to find a policy that maximizes the expected return given the model and its uncertainties. It is often believed that this optimization can be tractable only if analytical, gradient-based algorithms are used; however, these algorithms require using specific families of reward functions and policies, which greatly limits the flexibility of the overall approach. We introduced a novel model-based RL algorithm [23], called Black-DROPS (Black-box Data-efficient RObot Policy Search), that: (1) does not impose any constraint on the reward function or the policy (they are treated as black-boxes), (2) is as data-efficient as the state-of-the-art algorithm for data-efficient RL in robotics, and (3) is as fast (or faster) than analytical approaches when several cores are available. The key idea is to replace the gradient-based optimization algorithm with a parallel, black-box algorithm that takes into account the model uncertainties. We demonstrate the performance of our new algorithm on two standard control benchmark problems (in simulation) and a low-cost robotic manipulator (with a real robot).

Publications: [23]

7.1.4.2. Reset-free Data-efficient Trial-and-error for Robot Damage Recovery

Participants: Konstantinos Chatzilygeroudis, Jean-Baptiste Mouret, Vassilis Vassiliades.

The state-of-the-art RL algorithms for robotics require the robot and the environment to be reset to an initial state after each episode, that is, the robot is not learning autonomously. In addition, most of the RL methods for robotics do not scale well with complex robots (e.g., walking robots) and either cannot be used at all or take too long to converge to a solution (e.g., hours of learning). We introduced a novel learning algorithm called “Reset-free Trial-and-Error” (RTE) that (1) breaks the complexity by pre-generating hundreds of possible behaviors with a dynamics simulator of the intact robot, and (2) allows complex robots to quickly recover from damage while completing their tasks and taking the environment into account [13]. We evaluated our algorithm on a simulated wheeled robot, a simulated six-legged robot, and a real six-legged walking robot that are damaged in several ways (e.g., a missing leg, a shortened leg, faulty motor, etc.) and whose objective is to reach a sequence of targets in an arena. Our experiments show that the robots can recover most of their locomotion abilities in an environment with obstacles, and without any human intervention.

Publications: [13]

7.1.5. Illumination & Quality Diversity Algorithms

7.1.5.1. Using Centroidal Voronoi Tessellations to Scale up the MAP-Elites Algorithm

Participants: Konstantinos Chatzilygeroudis, Jean-Baptiste Mouret, Vassilis Vassiliades.

The MAP-Elites algorithm [55] is a key step of our "Intelligent Trial and Error" approach [46] for data-efficient damage recovery. It works by discretizing a continuous feature space into unique regions according to the desired discretization per dimension. While simple, this algorithm has a main drawback: it cannot scale to high-dimensional feature spaces since the number of regions increase exponentially with the number of dimensions. We addressed this limitation by introducing a simple extension of MAP-Elites that has a constant, pre-defined number of regions irrespective of the dimensionality of the feature space [21]. Our main insight is that methods from computational geometry could partition a high-dimensional space into well-spread geometric regions. In particular, our algorithm uses a centroidal Voronoi tessellation (CVT) to divide the feature space into a desired number of regions; it then places every generated individual in its closest region, replacing a less fit one if the region is already occupied. We demonstrated the effectiveness of the new "CVT-MAP-Elites" algorithm in high-dimensional feature spaces through comparisons against MAP-Elites in maze navigation and hexapod locomotion tasks.

Publications: [21], [37], [38]

7.1.5.2. Aerodynamic Design Exploration through Surrogate-Assisted Illumination

Participants: Adam Gaier, Jean-Baptiste Mouret.

Design optimization techniques are often used at the beginning of the design process to explore the space of possible designs. In these domains, illumination algorithms, such as MAP-Elites, are promising alternatives to classic optimization algorithms because they produce diverse, high quality solutions in a single run, instead of a single, near-optimal solution. Unfortunately, these algorithms currently require a large number of function evaluations, limiting their applicability. In our recent work [27], [26], we introduced a new illumination algorithm, called Surrogate-Assisted Illumination (SAIL), that creates a map of the design space according to user-defined features by leveraging surrogate modeling and intelligent sampling to minimize the number of evaluations. On a 2-dimensional airfoil optimization problem SAIL produces hundreds of diverse but high performing designs with several orders of magnitude fewer evaluations than MAP-Elites [55] or CMA-ES [52]. As shown in this article, SAIL can also produce maps of high-performing designs in a more realistic 3-dimensional aerodynamic task with an accurate flow simulation. Overall, SAIL can help designers understand what is possible, beyond what is optimal, by considering more than pure objective-based optimization.

Publications: [27], [26]

7.1.6. Applications – civil robotics

7.1.6.1. Minimally Invasive Exploration of Heritage Buildings

Participants: Jean-Baptiste Mouret, Lucien Renaud, Kapil Sawant.

In 2017, the team officially joined the ScanPyramids mission, which aims at better understanding how the pyramids of the Old Kingdom were built, but also to encourage innovations in various fields (muography, virtual reality, simulation, ...) that could be useful for the pyramids as well as for other monuments. The ScanPyramids team has discovered several previously unknown voids in the pyramid of Cheops, one of them with a size similar to the one of the Grand Gallery, called « ScanPyramids' Big Void ».

We participated to the article about the ScanPyramids' Big Void [17] and we designed several prototypes for minimally invasive exploration. We envision exploration to take place in two stages. At first, a tubular robot fitted with an omnidirectional camera would be inserted to take high-resolution pictures of the inaccessible place. In a second stage, the team would use the same hole to send an exploration robot operated remotely to travel through corridors and help mapping the interior. For this second step, we are currently designing a miniature blimp that would be folded during the insertion, then remotely inflated once in the inaccessible place. When the exploration is over, the blimp would come back to its base, be deflated, then extracted from the insertion hole.

Publications: [17]

7.1.7. Humanoid Robotics

7.1.7.1. Trial-and-error Learning of Repulsors for Humanoid QP-based Whole-Body Control

Participants: Karim Bouyarmane, Serena Ivaldi, Jean-Baptiste Mouret, Jonathan Spitz, Vassilis Vassiliades.

Whole body controllers based on quadratic programming allow humanoid robots to achieve complex motions. However, they rely on the assumption that the model perfectly captures the dynamics of the robot and its environment, whereas even the most accurate models are never perfect. We introduced a trial-and-error learning algorithm that allows whole-body controllers to operate in spite of inaccurate models, without needing to update these models [35]. The main idea is to encourage the controller to perform the task differently after each trial by introducing repulsors in the quadratic program cost function. We demonstrated our algorithm on (1) a simple 2D case and (2) a simulated iCub robot for which the model used by the controller and the one used in simulation do not match.

Publications: [35]

7.1.7.2. Safe Trajectory Optimization for Whole-body Motion of Humanoids

Participants: Serena Ivaldi, Valerio Modugno.

Multi-task prioritized controllers generate complex behaviors for humanoids that concurrently satisfy several tasks and constraints. In our previous work we automatically learned the task priorities that maximized the robot performance in whole-body reaching tasks, ensuring that the optimized priorities were leading to safe behaviors. Here, we take the opposite approach: we optimize the task trajectories for whole-body balancing tasks with switching contacts, ensuring that the optimized movements are safe and never violate any of the robot and problem constraints. We use (1+1)-CMA-ES with Constrained Covariance Adaptation as a constrained black box stochastic optimization algorithm, with an instance of (1+1)- CMA-ES for bootstrapping the search. We apply our learning framework to the prioritized whole-body torque controller of iCub, to optimize the robot's movement for standing up from a chair.

Publications: [29]

7.1.7.3. Humanoid Robot Fall Control

Participant: Karim Bouyarmane.

Falling is a major skill to be mastered by an autonomous humanoid robot, since no matter what balance controller we use, a humanoid robot will end up falling in certain circumstances. We proposed new approaches to control humanoid robots in general fall configurations and in general cluttered environment. From fall detection instant, a pre-imapct phase is triggered where a real-time configuration adaptation routine makes the robot quickly analyze the surrounding environment, choose best impact points on the environment, and adapts its configuration accordingly to meet the desired impact points (all calculations performed in the short duration of 0.7s to 1s that the fall lasts). Then right after impact a real-time motor PD gain adaptation controller allows to set the right values for the gains in real-time to comply actively with the impact while minimizing peak torque at impact. Finally, a model-predictive approach combined with a novel formulation of admissible force polytopes accounting for both torque limits and Coulomb friction limitation ensures that the robot safely comes to a steady-state resting state at the end of the fall.

Publications: [41], [34], [33]

7.1.7.4. Stability Proof of Weighted Multi-Task Humanoid QP Controller

Participant: Karim Bouyarmane.

We proved that weighted multi-task controllers are locally exponentially stable under appropriate conditions of the task gain matrices. We also derived a number of stability properties of the underlying QP optimization problem.

Publications: [12]

7.1.7.5. *Theoretical Study of Commonalities between Locomotion and Manipulation in Humanoid-like Locomotion-and-manipulation Integration System*

Participant: Karim Bouyarmane.

We published our theoretical study on common ground formulations of locomotion and manipulation, and thereby their extension to integrated locomotion-and-manipulation systems, by analytically deriving their planning and control solutions in low-dimensional proof-of-concept examples based on nonlinear control and differential geometry tools.

Publications: [11]

7.1.8. *Embodied Evolutionary Robotics*

7.1.8.1. *Online Distributed Learning for a Swarm of Robots*

Participants: Iñaki Fernández Pérez, Amine Boumaza, François Charpillet.

We study how a swarm of robots adapts over time to solve a collaborative task using a distributed Embodied Evolutionary approach, where each robot runs an evolutionary algorithm and locally exchange genomes and fitness values. Particularly, we study a collaborative foraging task, where the robots are rewarded for collecting food items that are too heavy to be collected individually and need at least two robots to be collected. Furthermore, to promote collaboration, agents must agree on a signal in order to collect the items. Our experiments show that the distributed algorithm is able to evolve swarm behavior to collect items cooperatively. The experiments also reveal that effective cooperation is evolved due mostly to the ability of robots to jointly reach food items, while learning to display the right color that matches the item is done suboptimally. However, a closer analysis shows that, without a mechanism to avoid neglecting any kind of item, robots collect all of them, which means that there is some degree of learning to choose the right value for the color effector depending on the situation.

This work was carried through the PhD Thesis of Iñaki Fernández Pérez under the supervision of François Charpillet and Amine Boumaza. This thesis was defended on the 19th December 2017.

Publications: [25]

7.1.8.2. *Phylogeny of Embodied Evolutionary Robotics*

Participant: Amine Boumaza.

We explore the idea of analyzing Embodied Evolutionary Robotics from the perspective of genes and their dynamics using phylogenetic trees. We illustrate a general approach on a simple question regarding the dynamics of the fittest and most copied genes as an illustration using tools from spectral graph theory or computational phylogenetics, and argue that such an approach may give interesting insights on the behavior of these algorithms. This idea seems promising and further investigations are underway, especially on the links with coalescence theory.

Publications: [22]

7.2. Natural Interaction with Robotics Systems

7.2.1. *Control of Interaction*

7.2.1.1. *Towards Human-aware Whole-Body Controllers for Physical Human-Robot Interaction*

Participants: Oriane Dermy, Serena Ivaldi.

The success of robots in real-world environments is largely dependent on their ability to interact with both humans and said environment. The FP7 EU project CoDyCo focused on the latter of these two challenges by exploiting both rigid and compliant contacts dynamics in the robot control problem. Regarding the former, to properly manage interaction dynamics on the robot control side, an estimation of the human behaviours and intentions is necessary. We contributed to the building blocks of such a human-in-the-loop controller, and validate them in both simulation and on the iCub humanoid robot for the final demo of the CoDyCo project where a human assists the robot in standing up from being seated on a bench.

The controller is the basis for our current researches in the AnDy project.

Publications: [20]

7.2.1.2. Generating Motions for a Humanoid Robot that Assists a Human in a Co-manipulation Task

Participants: Karim Bouyarmane, Kazuya Otani, Serena Ivaldi.

We proposed a method to make a humanoid robot adapt its motion to help a human collaborator in simulation realize a collaborative manipulation task with the robot while the robot figures out its configuration in real-time through symmetric retargeting.

Publications: [40]

7.2.1.3. Human-to-humanoid Motion Retargeting

Participants: Karim Bouyarmane, Kazuya Otani.

We continue the development of our human-to-humanoid motion retargeting method by extending it to whole-body manipulation motions based on our previously-proposed multi-robot QP paradigm. The motion retargeting system is now able to autonomously adapt the motion of the robot to dynamics parameters of the manipulated object that substantially differ from those used to provide the human demonstration.

Publications: [31]

7.2.2. Non-verbal Interaction

7.2.2.1. Multimodal Prediction of Intention via Probabilistic Movement Primitives (ProMP)

Participants: François Charpillet, Oriane Dermy, Serena Ivaldi.

We designed a method for predicting the intention of a user interacting (physically or not) with the humanoid robot iCub, and implemented an associated open-source software (cf. ProMP_iCub in the Software section). Our goal is to allow the robot to infer the intention of the human partner during collaboration, by predicting the future intended trajectory: this capability is critical to design anticipatory behaviors that are crucial in human–robot collaborative scenarios, such as in co-manipulation, cooperative assembly, or transportation. We propose an approach to endow the iCub with basic capabilities of intention recognition, based on Probabilistic Movement Primitives (ProMPs), a versatile method for representing, generalizing, and reproducing complex motor skills. The robot learns a set of motion primitives from several demonstrations, provided by the human via physical interaction. During training, we model the collaborative scenario using human demonstrations. During the reproduction of the collaborative task, we use the acquired knowledge to recognize the intention of the human partner. Using a few early observations of the state of the robot, we can not only infer the intention of the partner but also complete the movement, even if the user breaks the physical interaction with the robot. We evaluated our approach both in simulation and with the real iCub robot. We also proposed a method to exploit referential gaze and combine it with physical interaction, to improve the prediction of primitives. The software implementing our approach is open source and available on the GitHub platform. In addition, we provide tutorials and videos.

Publications: [15]

7.2.2.2. PsyPhINe: Cogito Ergo Es

Participant: Amine Boumaza.

PsyPhINe is an interdisciplinary and exploratory project (see 9.1.2) 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?

This year an experimental campaigns was organized in which around 40 test subjects where asked to solve a task in front of the moving robotic device. These interactions were recorded on video along with eye tracking data. To analyze the data, a web application was created that crowd-sources video annotation to internet users. A preliminary analysis of the data was presented at the third 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 10.1.1.1).

7.2.2.3. Active 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. However, the robot movements are typically fixed or they obey heuristic strategies, such as turning the head and moving towards the source, which may be suboptimal. This work proposes an approach to control the robot movements so as to locate the source as quickly as possible using the Monte-Carlo Tree Search algorithm [30]. We represent the belief about the source using our 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.

This work was carried through the PhD Thesis of Van Quan Nguyen under the supervision of Emmanuel Vincent and Francis Colas. This thesis was defended on the 3rd November 2017.

Publication: [30]

8. Bilateral Contracts and Grants with Industry

8.1. Cifre Diatelic-Pharmagest

Participants: François Charpillet, Yassine El Khadiri, Cedric Rose, Gabriel Corona.

Cedric Rose and Gabriel Corona are from Diatelic.

The ageing of the population and the increase in life expectancy will confront modern societies with an unprecedented demographic transformation. The placement of older people in a nursing home (EPHAD) is often only a choice of reason and can be rather poorly experienced by people. One answer to this societal problem is the development of Smart home technologies that facilitate elderly to stay in their homes longer than they can do today. This new collaboration with Diatelic a subsidiary of the Pharmagest group is supported through a PhD thesis (Cifre) which started in june 2017. The objective is to enhance the CareLib solution developed by Diatelic and Larsen Team through a previous collaboration (Satelor project). The Carelib offer is a solution, consisting of

- a connected box (with touch screen),
- a 3D sensor (capable (1)to measure characteristics of the gait such as the speed and step length, (2) to identify Activities of Daily Life and (3) to detect emergency situation such as Fall,
- universal sensors (motion, ...) installed in each part of the housing.

The objective of the PhD program is to provides personalized follow-up by learning life habits, the main objective being to track the Activities of Daily Life (ADL) and detect emergency situations needing external interventions (E.G fall detection). This year we have developed an algorithm capable to detect sleep-wake cycles using only motion sensors. The approach is based on bayesian inference. The algorithms have been evaluated using publicly available dataset and Diatelic's own dataset.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. SATELOR

Title: SATELOR

Program: AME Region Lorraine

Duration: September 2013 - September 2017

Coordinator: Diatelic

PI for Inria: François Charpillet

The 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.

Publications: [16], [18]

9.1.2. Project PsyPhINe: Cogitamus ergo sumus

Title: Cogitamus ergo sumus

Program: PEPS CNRS

Duration: January 2016 - January 2018

Coordinator: MSH Lorraine (USR3261)

Larsen member: Amine Boumaza

This project gathers researchers from the following institutes: InterPsy (EA 4432), APEMAC, EPSaM (EA4360), Archives Henri-Poincaré (UMR7117), Inria Bordeaux Sud-Ouest, Loria (UMR7503). Refer to sec. 7.2.2.2 for the goals of the project.

9.2. European Initiatives

9.2.1. FP7 & H2020 Projects

9.2.1.1. RESIBOTS

Title: Robots with animal-like resilience

Program: 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 damages 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, nor 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 open new research avenues for adaptive machines.

9.2.1.2. CODYCO

Title: Whole-body Compliant Dynamical Contacts for Humanoids

Programme: FP7

Type: ICT STREP (No. 600716)

Duration: March 2013 - February 2017

Coordinator: IIT

PI for Inria: Serena Ivaldi

The aim of CoDyCo was to improve the current control and cognitive understanding about robust, goal-directed whole-body motion interaction with multiple contacts. CoDyCo went beyond traditional approaches: proposing methodologies for performing coordinated interaction tasks with complex systems; combining planning and compliance to deal with predictable and unpredictable events and contacts; validating theoretical progresses in real-world interaction scenarios. CoDyCo advanced the state-of-the-art in the way robots coordinate physical interaction and physical mobility.

9.2.1.3. ANDY

Title: Advancing Anticipatory Behaviors in Dyadic Human-Robot Collaboration

Programme: H2020

Type: ICT RIA (No. 731540)

Duration: January 2017 - December 2020

Coordinator: IIT

PI for Inria: Serena Ivaldi

Recent technological progress permits robots to actively and safely share a common workspace with humans. Europe currently leads the robotic market for safety-certified robots, by enabling robots to react to unintentional contacts. AnDy leverages these technologies and strengthens European leadership by endowing robots with the ability to control physical collaboration through intentional interaction.

To achieve this interaction, AnDy relies on three technological and scientific breakthroughs. First, AnDy will innovate the way of measuring human whole-body motions by developing the wearable AnDySuit, which tracks motions and records forces. Second, AnDy will develop the AnDyModel, which combines ergonomic models with cognitive predictive models of human dynamic behavior in collaborative tasks, which are learned from data acquired with the AnDySuit. Third, AnDy will propose the AnDyControl, an innovative technology for assisting humans through predictive physical control, based on AnDyModel.

By measuring and modeling human whole-body dynamics, AnDy provides robots with an entirely new level of awareness about human intentions and ergonomy. By incorporating this awareness online in the robot's controllers, AnDy paves the way for novel applications of physical human-robot collaboration in manufacturing, health-care, and assisted living.

AnDy will accelerate take-up and deployment in these domains by validating its progress in several realistic scenarios. In the first validation scenario, the robot is an industrial collaborative robot, which tailors its controllers to individual workers to improve ergonomy. In the second scenario, the robot is an assistive exoskeleton which optimizes human comfort by reducing physical stress. In the third validation scenario, the robot is a humanoid, which offers assistance to a human while maintaining the balance of both.

Partners: Italian Institute of Technology (IIT, Italy, coordinator), Josef Stefan Institute (JSI, Slovenia), DLR (Germany), IMK Automotive Gmbh (Germany), XSens (Netherlands), AnyBody Technologies (Denmark)

9.3. International Research Visitors

9.3.1. Visits of International Scientists

9.3.1.1. Internships

- Waldez Azevedo Gomes Junior (Brazil) – from May 2017 to November 2017
- Kazuya Otani (USA, Carnegie Mellon) – from May 2017 to November 2017
- Kapil Sawant (India, BITS Pilani) – from July to December 2017
- Luigi Penco (Italy, La Sapienza University) – from October 2017 to February 2018

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

- Co-organized an international workshop at IROS 2017 (*Micro-Data Learning: the next frontier of Robot Learning?*) [Jean-Baptiste Mouret].
- Co-organized an international workshop at ECAL'2017 (*Evolution in Physical System*) [Jean-Baptiste Mouret].
- Co-organized an international workshop at HUMANOIDS 2017 (*Human-Humanoid collaboration: the next industrial revolution?*) [Serena Ivaldi].
- Co-organized "Expressions, simulations, perceptions - Journées PsyPhINe 2017", the third workshop of the PsyPhINe project (http://poincare.univ-lorraine.fr/fr/manifestations/psyphine-2017) [Amine Boumaza].

10.1.1.2. Member of the Organizing Committees

- Serena Ivaldi was Publicity Chair of the international conferences HUMANOIDS 2017 (IEEE/RSJ International Conference on Humanoid Robots) and of ICDL 2017 (IEEE Conference on Development and Learning)

10.1.2. Scientific Events Selection

10.1.2.1. Member of Conference Program Committees

- CEC 2017 (Congress on Evolutionary computation) [Amine Boumaza]
- CoRL (Conference on Robot Learning) [Serena Ivaldi, Jean-Baptiste Mouret]

- ECAL 2017 (European Conference on Artificial Life) [Amine Boumaza, Jean-Baptiste Mouret]
- EVO* 2017 (EvoStar) [Jean-Baptiste Mouret]
- GECCO2017 (Genetic and Evolutionary Computation Conference) [Amine Boumaza, Jean-Baptiste Mouret]
- HFR 2017 (Human-Friendly Robotics Conference) [Serena Ivaldi]
- HUMANOIDS 2017 (IEEE/RSJ International Conference on Humanoid Robots) [Serena Ivaldi, associate editor]
- ICRA 2017 & ICRA 2018 (IEEE International Conference on Robotics and Automation) [Serena Ivaldi, associate editor]
- IROS 2017 (IEEE/RSJ International Conference on Intelligent Robots and Systems) [Serena Ivaldi, associate editor]
- JFPDA 2017 (Journée Francophones sur la Planification, la Décision et l'Apprentissage pour la conduite de systèmes) [Vincent Thomas]
- NIPS Bayesian Optimization Workshop [Jean-Baptiste Mouret]

10.1.2.2. Reviewer for Peer-reviewed Conferences

- ICRA 2018 (2018 IEEE International Conference on Robotics and Automation) [Karim Bouyarmane, Francis Colas, Serena Ivaldi, Jean-Baptiste Mouret]
- IROS 2017 (IEEE/RSJ International Conference on Intelligent Robots and Systems) [Karim Bouyarmane, Francis Colas, Jean-Baptiste Mouret]
- HUMANOIDS 2017 (IEEE/RSJ International Conference on Humanoid Robots) [Jean-Baptiste Mouret, Karim Bouyarmane]
- ICDL-EPIROB 2017 (EEE International Conference on Development and Learning and on Epigenetic Robotics) [Francis Colas]

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- Jean-Baptiste Mouret co-edited a special issue of the Artificial Life journal (MIT Press), called "Evolution in Physical Systems" [19]
- Serena Ivaldi was an Associate Editor of IEEE Robotics and Automation Letters (RAL) and an Editorial Board member for the Springer Journal of Intelligent Service Robotics

10.1.3.2. Reviewer - Reviewing Activities

- Frontiers in AI and Robotics [Amine Boumaza, Serena Ivaldi, Jean-Baptiste Mouret]
- Robotics and Automation Letters [Karim Bouyarmane, Francis Colas, Jean-Baptiste Mouret]
- Autonomous Robots [Francis Colas]
- IEEE Transactions on Robotics [Karim Bouyarmane, Serena Ivaldi]
- International Journal of Robotics Research [Karim Bouyarmane]
- IEEE Transactions on Systems, Man and Cybernetics [Karim Bouyarmane]

10.1.4. Invited Talks

- Jean-Baptiste Mouret was invited to talk at as the Centre for BioRobotics – University of Southern Denmark (distinguished speaker), at the LIRIS (CNRS / Univ. Lyon) at the "Evolution in Cognition Workshop" (GECCO 2017), and at the GT8 (Robotique et Neurosciences) meeting of the GDR Robotique (CNRS).
- Serena Ivaldi was invited to talk at XEROX Research in Grenoble, at IHEST in Paris, at the GT Robotique Humanoide in Montpellier, at the IEEE ICDL 2017 Workshop on Perception of Self, and at the the GT8 (Robotique et Neurosciences) meeting of the GDR Robotique (CNRS).

- Karim Bouyarmane was invited to give a presentation at the Seminaire Francilien de Geometrie Algorithmique et Combinatoire at Institut Henri Poincarre in Paris.

10.1.5. 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”.
- Serena Ivaldi is the co-chair of the web task force of the IEEE technical committee “Developmental and Cognitive Systems”.

10.1.6. Scientific Expertise

- Serena Ivaldi was vice-president of the CES33 committee for evaluation of national projects for the ANR
- Francis Colas was member of the CES33 committee for evaluation of national projects for the ANR
- Serena Ivaldi is a member of the scientific experts committee for the upcoming Robots exhibition at the Cite de la Science in Paris.
- François Charpillet was member of the hiring committees:
  - CR2 Inria: Committee member (Bordeaux)
  - Maitre de conferences: Committee member for jury (UTT)
  - Professeur des Universités: Committee member for jury PR 4036 “Traitement du signal, conception de méthodes de décision, fusion de données” (UTT)

10.1.7. Research Administration

- Amine Boumaza is a board member of the Évolution Artificielle association.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Master [Vincent Thomas]

- “Modèles probabilistes et Apprentissage par renforcement”, 15h eq. TD, M2 “Informatique - Image Perception Raisonnement Cognition”, Univ. Lorraine, France.
- “Optimisation et méta-heuristiques”, 15h eq. TD, M1 “Informatique”, Univ. Lorraine, France.
- ‘Game Design”, 20h eq. TD, M1 “Sciences Cognitives”, Univ. Lorraine, France.
- “Agent intelligents et collectifs”, 20h eq. TD, M1 “Sciences Cognitives”, Univ. Lorraine, France.
- “Serious Game”, 12h eq. TD, M2 “Sciences Cognitives”, Univ. Lorraine, France.
- “Robotique Autonome”, 18h eq. TD, M2 “Systèmes Interactifs et Robotiques”, CentraleSupélec, France.

Formation IHEST [Serena Ivaldi] “Robotique collaborative”, 2h.

Tutorial in an international conference [Jean-Baptiste Mouret] “Evolutionary Robotics”, GECCO 2017, Berlin, Germany [1h].

Engineering School [Karim Bouyarmane]:

- “Programmation et algorithmique Java”, Polytech Nancy School of Engineering
- Engineering school: Karim Bouyarmane, “Langages C et C++”, Polytech Nancy School of engineering
- Engineering school: Karim Bouyarmane, “Introduction to Computer Science”, Polytech Nancy School of engineering

- Engineering school: Karim Bouyarmane, “Operating Systems”, Polytech Nancy School of engineering

10.2.2. Supervision

- HDR: Francis Colas, “*Modélisation bayésienne et robotique*”, 17 May 2017 [7].
- PhD: Van Quan Nguyen, “*Mapping of a sound environment by a mobile robot*”, 3 Nov. 2017, Emmanuel Vincent (advisor), Francis Colas, François Charpillet.
- PhD: Nassim Kaldé, “*Exploration et reconstruction d’un environnement inconnu par une flottille de robots*”, 12 Dec. 2017, François Charpillet (advisor), Olivier Simonin.
- PhD: Iñaki Fernández Pérez, “*Apprentissage incrémental évolutionnaire*”, 19 Dec. 2017, F. Charpillet (advisor), Amine Boumaza.
- PhD: Vincent Samy, “*Humanoid fall control by postural reshaping and adaptive compliance*”, 13 Nov. 2017, Abderrahmane Kheddar (advisor), Karim Bouyarmane.
- PhD in progress: Yassine El Khadiri, “Apprentissage automatique pour l’assistance à l’autonomie à domicile”, started in June 2017, François Charpillet (advisor).
- PhD in progress: Adrien Malaisé, “*Capteurs porte´s dans la robotique collaborative : de l’apprentissage du mouvement humain a` l’acceptabilite´ de cette technologie*”, started in January 2017, Francis Colas (advisor), Serena Ivaldi
- PhD in progress: Adam Gaier ,“*Optimisation aerodynamic design through illumination of surrogate models*”, started in June 2017, Jean-Baptiste Mouret (advisor), Alexander Asteroth.
- PhD in progress: Rituraj Kaushik, “Fast adaptation to damage by exploiting trajectory data”, started in Oct. 2016, Jean-Baptiste Mouret (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: Adrian Bourgaud, “*Multi-sensor Fusion and Active Sensing*”, started in Jul. 2015, François Charpillet (advisor).

10.2.3. Juries

- Jean-Baptiste Mouret was:
  - a reviewer of the PhD of Valerio Modugno (Univ. Sapienza, Rome, Italy);
  - the president of the jury for the PhD of Charles Rocabert (Univ. Lyon / Inria).
- Serena Ivaldi was
  - an examiner of the PhD of Ganna Pugach (Univ. Cergy-Pontoise);
  - a reviewer of the PhD of Oskar Palinko (IIT & Univ. Genoa, Italy);
  - an external reviewer in the VIVA / PhD exam of Valerio Ortenzi (Univ. of Birmingham, UK).
- François Charpillet was:
  - a reviewer of the PhD of Kabalan Chaccour (Tech. Univ. Belfort-Montbéliard);
  - a reviewer of the PhD of Alexis Brenon (Univ. Grenoble Alpes);
  - a reviewer of the PhD of Chu Xing (Ecole Centrale Lille);
  - a reviewer of the PhD of Viet-Cuong Ta (Univ. Grenoble Alpes);
  - an examiner of the HDR of Olivier Buffet (Univ. Lorraine).

10.3. Popularization

One of the main general audience event of the team has been the “Fête de la Science” on the 13th and 14th of October, 2017. The team hosted about 10 groups of 15-20 persons (150 to 200 visitors) over two days, with the following demonstrations:

- “smart appartment”, with the “smart tiles” and the Pepper Robot;
- AnDy project: activity recognition with the “inertial” motion capture suit, muscle sensing with EMG sensors;
- iCub robot: performing squats with the iCub robot and a whole-body motion controller; interactive demonstrations of iCub following a red-ball (given to a child) with the gaze and the head;
- ResiBots project: damage recovery with a damaged 6-legged robot.

The team also presented numerous videos of additional results with the robots. Involved members of the team: François Charpillet, Konstantinos Chatzilygeroudis, Brice Clément, Francis Colas, Oriane Dermy, Dorian Goepp, Waldez Gomes, Aurore Husson, Serena Ivaldi, Yassine El Khadiri, and Adrian Bourgaud, Adrien Malaisé, Jean-Baptiste Mouret, Kazu Otani and Olivier Rochel.

In addition:

- Vincent Thomas gave tutorials on “physics simulation” and “stochastic decision making” for teachers during “journées ISN-EPI” (30th of Mars 2017).
- Vincent Thomas participated in the preparation and reviewing of “Computer Science Exporoute” (conducted by Inria Nancy Grand-Est) presented in 2017.
- Vincent Thomas animated discussions and tutorials on “planning in mazes” for students from 6 to 20 years old during “fetes de la sciences” organized by Univ. Lorraine (13th of October 2017).
- Vincent Thomas presented “Bayesian reasonning” during “journées portes ouvertes” organized by Inria Nancy-Grand Est (14th of October 2017).
- Vincent Thomas accompanied computer science DUT students during the “Nancy acceuille Google” event (20th of October 2017).
- Serena Ivaldi was panelist in public conferences/debates in Futur en Seine and 50 ans of Inria, both in Paris.
- Amine Boumaza is a member of the editorial board of “Interstice”.
- Karim Bouyarmane was the academic advisor for the Polytech School of Engineering students team of robotics that particpated to the 2017 Coupe de France de Robotique.
- Francis Colas participated in a Sciences en Lumières event “Visages de la robotique” at RTE (14th of December 2017).

11. 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.

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[7] F. COLAS.*Modélisation bayésienne et robotique*, Université de Lorraine, May 2017, Habilitation à diriger des recherches, https://hal.inria.fr/tel-01647934.

[8] V. Q. NGUYEN.*Mapping of a sound environment by a mobile robot*, University of Lorraine, November 2017, https://hal.archives-ouvertes.fr/tel-01664540.

Articles in International Peer-Reviewed Journal

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A. GAIER, A. ASTEROTH, J.-B. MOURET.*Data-Efficient Exploration, Optimization, and Modeling of Diverse Designs through Surrogate-Assisted Illumination*, in "Genetic and Evolutionary Computation Conference (GECCO 2017)", Berlin, Germany, 2017, https://arxiv.org/abs/1702.03713 [*DOI :* 10.1145/3071178.3071282], https://hal.inria.fr/hal-01518698.

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Team MADYNES

Management of dynamic networks and services

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
Networks and Telecommunications

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Creation of the Project-Team: 2004 February 01, updated into Team: 2017 January 19, end of the Team: 2017 December 31

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1. Personnel

Research Scientists

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Xavier Marchal [CNRS]
Thomas Paris [Univ de Lorraine]
Abdulqawi Saif [Xilopix, granted by CIFRE]
Nicolas Schnepf [Inria]
Salvatore Signorello [University of Luxembourg - Univ. Lorraine (co-advising)]
Evangelia Tsiontsiou [Univ de Lorraine, until Oct 2017]
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Visiting Scientists

Juan Pablo Afman [Univ de Lorraine, from May 2017 until Jul 2017]
Thomas Gurriet [from May 2017 until Jul 2017]

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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. Application Domains

4.1. Mobile and constrained networks

The results coming out from MADYNES can be applied to any dynamic infrastructure that contributes to the delivery of value added services. While this is a potentially huge application domain, we mainly focus at the network level on mobile devices and Internet of Things. We are investigating the provisioning, monitoring, configuration and performance management issues.

4.2. Dynamic services infrastructures

At the service level, dynamics is also increasing very fast. We apply the results of our work on autonomous management on infrastructures which support dynamic composition and for which self-instrumentation and management automation is required. The target service environments are:

- sensor networks,
- cyber-physical systems,
- information centric networks,
- distributed cloud environnements,
- smart environments.

5. Highlights of the Year

5.1. Highlights of the Year

- The team (Jérôme François and Lucas Nussbaum) organized the Cloud Days (GdR CNRS RSD, Virtualizaion and Cloud Action) in Loria (Nancy).
- Loic Rouch demonstrated in Blackhat Europe 2017 an attack to tack over a z-wave network https://www.blackhat.com/eu-17/briefings/schedule/#a-universal-controller-to-take-over-a-z-wave-network-8459.

BEST PAPER AWARD :
[17] **IFIP/IEEE Symposium on Integrated Network and Service Management (IM) - AnNet workshop**. S. LAGRAA, J. FRANCOIS.

6. New Software and Platforms

6.1. 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 - Université de Lorraine - Loria - Grid'5000 - Inria
- Contact: Lucas Nussbaum
- URL: http://distem.gforge.inria.fr

6.2. 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: Arthur Garnier, Clement Parisot, Émile Morel, Emmanuel Jeanvoine, Jérémie Gaidamour, Luc Sarzyniec and Lucas Nussbaum
- Contact: Lucas Nussbaum
- URL: https://www.grid5000.fr/

6.3. 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, Luc Sarzyniec and Lucas Nussbaum
- Partners: CNRS - Université de Lorraine - Loria - Grid'5000 - Inria
- Contact: Lucas Nussbaum
- URL: http://kadeploy3.gforge.inria.fr

6.4. MECSYCO-RE-C++

en Multi-agent Environment for Complex SYstems COsimulation. Coeur C++
KEYWORDS: Agent - Multi-agent - Multi-model - Simulator - Simulation - Modeling - 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 vizualizaing simulations).

- Participants: Benjamin Camus, Benjamin Segault, Julien Vaubourg, Laurent Ciarletta, Nicolas Kirchner, Victorien Elvinger, Vincent Chevrier and Yannick Presse
- Partners: Université de Lorraine - Inria
- Contact: Vincent Chevrier

6.5. MECSYCO-RE-java

Multi-agent Environment for Complex SYstems COsimulation. Coeur java
KEYWORDS: Agent - Multi-agent - Co-simulation - Multi-model - Simulator - Simulation - Modeling - 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 complemented by mecsyco-com (a communication package for distributed exécution) and mecsyco-visu (a set of tools for vizualizaing simulations).

- Participants: Benjamin Camus, Christine Bourjot, Julien Siebert, Julien Vaubourg, Laurent Ciarletta, Victorien Elvinger, Vincent Chevrier and Yannick Presse
- Partners: Université de Lorraine - Inria
- Contact: Vincent Chevrier
- URL: http://www.mecsyco.com

6.6. 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/

6.7. Platforms

6.7.1. CPS Security Assessment Platform

This year, we have extended our Cyber-Physical systems security assessment platform with new hardware components including multiple types of Programmable Logic Controllers (PLS) and a small scale distribution and sorting testbed. The physical platform is also extended with several IoT devices dedicated to residential networks (heating control, lightning system, home gateways, etc). The platform will be mainly used for building security assessmenet and evaluation experimentation on the available devices to identify and validate their associated attack patterns and discover new vulnerabilities.

7. New Results

7.1. Monitoring

7.1.1. Quality of Experience Monitoring

Participants: Isabelle Chrisment [contact], Thibault Cholez, Vassili Rivron, Lakhdar Meftah [University of Lille].

We have pursued our work on smartphone usage monitoring with the SPIRALS team (Inria/Université de Lille) and more specifically on proposing new methods to help measure the QoE and to protect the user's privacy when collecting such data.

In parallel, to evaluate our methods, we need a testing framework to automate testing of WiFi P2P mobile apps at scale. In [20] we proposed AndroFleet, a large-scale WiFi P2P testing framework. Androfleet can perform User Acceptance Testing for a fleet of emulators, by emulating the hardware behavior of the peer discovery, it gives the developers the ability to control P2P specific behaviors (peers joining and leaving).

7.1.2. Active Monitoring

Participants: Abdelkader Lahmadi [contact], Jérôme François, Frédéric Beck [LHS], Loic Rouch [LHS].

Following the work done in 2016, we pursued our collaboration with the regional PME TracIP (http://www.tracip.fr) on the development of attack assessment and forensics platform dedicated to industrial control systems. The platform involves multiple PLC from different manufacturers and real devices of factory automation systems (see 6.7.1).

During the year 2017, we have demonstrated that off-the-shelf hardware is sufficient to take over any Z-Wave network without knowing its topology or compromising any original devices and remaining unnoticeable for the primary controller. Our attack consists in building an adversary Z-Wave universal controller by reprogramming a mainstream USB stick controller. The technique exploits two features provided by the USB stick which allow (1) to set the network identifier (HomeID) and (2) to learn many devices identifiers even if they are not physically available. The attack has been demonstrated in Blackhat Europe 2017 by Loic Rouch (https://www.blackhat.com/eu-17/briefings/schedule/#a-universal-controller-to-take-over-a-z-wave-network-8459).

7.1.3. Service-level Monitoring of HTTPS traffic

Participants: Thibault Cholez [contact], Wazen Shbair, Jérôme François, Isabelle Chrisment.

We previously 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. In 2017, we finished to develop our solution to make it fully usable in real-time [1]. We now provide our prototype implementation (https://gitlab.inria.fr/swazen/HTTPSFirewall) in open-source. It operates by extending the iptables/netfilter architecture. It receives and demultiplexes the arriving HTTPS packets to a related flow. As soon as the number of packets in a given flow reaches a threshold, the identification engine extracts the features and runs the C4.5 algorithm to predict the HTTPS service of the flow.

7.1.4. Monitoring Programmable Networks

Participants: Jérôme François [contact], Olivier Festor, Paul Chaignon [Orange Labs], Kahina Lazri [Orange Labs], Thibault Delmas [Orange Labs].

Software-Defined Networking brings new capabilities in operating networks including monitoring. In the state-of-the art many proposals have been made to enhance monitoring of networks using OpenFlow or other proposed programmable frameworks. In a preliminary work [11], we reviewed them in order to highlight what are the remaining challenges to be addressed in that area. The main issue is the trade-off to be made between the strong expressibility (especially stateful operations) and capability of monitoring techniques that are necessary for advanced operation purposes and the complexity it induces if we want to keep the pace with line-rate packet processing. Another important aspect is the security as adding programmable monitoring functions may lead to introduce security threats. Our current work is thus focused on adding monitoring capacity while guaranteeing line-rate operations and safety requirements even when programs are deployed on running network switches.

7.1.5. Smart Contracts Monitoring

Participants: Jérôme François [contact], Sofiane Lagraa, Radu State [University of Luxembourg], Jérémy Charlier [University of Luxembourg].

Blockchain technologies are skyrocketing and the team is interested in assessing the impact of such technologies on networking, and if necessary managing the coupling between them. Indeed, blockchain efficiency resides in an overlay network built on top of a real infrastructure which needs to properly support it. Orchestrating network ressources, *i.e.* adding some network capacity, might be helpful but supposes first an in-depth monitoring of blockchain interactions. In a first work, we thus evaluated the relation among smart contracts. We defined methods to discover smart contracts interactions and the different group properties. This approach relies on graph modelling and mining techniques as well as tensor modelling combined with stochastic processes. It underlines actual exchanges between smart contracts and targets the predictions of future interactions among the communities. Comparative study between graph analysis and tensor analysis is provided for predictions of smart contract interactions. Finally, virtual reality visualization based on Unity 3D game engine has been applied [12].

7.1.6. Sensor networks monitoring

Participants: Rémi Badonnel, Isabelle Chrisment, Olivier Festor, Abdelkader Lahmadi [contact], Anthea Mayzaud.

Our work on IoT security monitoring has been published in IEEE Transactions on Network and Service Management [4]. This concerns more specifically our distributed monitoring architecture for detecting attacks against RPL networks. The RPL routing protocol has been standardized by IETF to enable a lightweight and robust routing in lower-power and lossy networks. After having compared existing IoT monitoring solutions, we have proposed a detection strategy for RPL version number attacks. This one relies on our monitoring architecture to preserve constrained node resources, in the context of AMI infrastructures. A versioning mechanism is incorporated into RPL in order to maintain an optimized topology. However, an attacker can exploit this mechanism to significantly damage the network and reduce its lifetime. We have exploited monitoring node collaboration to identify the attacker, the localization process being performed by the root after gathering detection information from all monitoring nodes. We have evaluated our solution through experiments and have analyzed the performance according to defined metrics. We have shown that the false positive rate of our solution can be reduced by a strategic monitoring node placement. We have also considered the scalability issue, by modeling this placement as an optimization problem and quantifying the number of required monitoring nodes to ensure acceptable false positive rates.

7.2. Security

7.2.1. Security analytics

Participants: Jérôme François [contact], Abdelkader Lahmadi, Sofiane Lagraa, Soline Blanc, Giulia de Santis, Olivier Festor, Radu State [University of Luxembourg], Christian Hammerschmidt [University of Luxembourg].

In 2017, we have continued our active cooperation with the High Security Lab (HSL) in Nancy. The latter provides the infrastructure to support two main projects in security analytics, namely the FUI HuMa project and the ATT AMICS. Thanks to darknet data of the HSL, we developped two methods based on graph-mining to extract knowledge. The first one focuses on port scanning analysis in order to profile the behaviours and patterns of attackers. By representing consecutive targeted ports in an aggregated graph format, we assess then the centrality of port number using different metrics and highlights valuable correlation among some of them. We are particularly able to identify patterns of scanning related to a specific setup (e.g. medical environment) [17]. We then extended this method to security events analysis by constructing multiple graphs to be analyzed with an outlier technique. The rationale is to represent individual behaviors and detect those which deviate from the majority. The method has been successfully applied to botnet detection in [16]. We are currently leveraging our graph analysis in order to provide to the community a new metric or distance to be applied when comparing port numbers. Indeed, numerical comparison is meaningless in that context and we could leverage either a semantic database (such as Wikipedia) or attacker database (darknet) to derive a meaningful metric, *i.e.* representing a real correlation between port numbers (TCP or UDP).

Furthermore, we continue our work on using Hidden Markov Models for analysing TCP scanning activities. We are now in a stage where individual models from different scanner tools or configurations (e.g. targeted ports) are used in order to automatically learn unique signatures then applied on non-labelled data.

7.2.2. NDN Security

Participants: Thibault Cholez [contact], Xavier Marchal, Olivier Festor, Jérôme François, Salvatore Signorello [University of Luxembourg], Radu State [University of Luxembourg], Samuel Marchal [Aalto University].

Information Centric Networking (ICN) is seen as a promising solution to re-conciliate the Internet usage with its core architecture. However, to be considered as a realistic alternative to IP, ICN must evolve from a pure academic proposition deployed in test environments to an operational solution in which security is assessed from the protocol design to its running implementation. Among ICN solutions, Named Data Networking (NDN), together with its reference implementation NDN Forwarding Daemon (NFD), acts as the most mature proposal but its vulnerability against the Content Poisoning Attack (CPA) is considered as a critical threat that can jeopardize this architecture. 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 a joint work with our colleagues from UTT and in the context of the ANR DOCTOR projet, we demonstrated through an experimental measurement campaign that CPA can easily and widely affect NDN. Our contribution is threefold: (1) we propose three realistic attack scenarios relying on both protocol design and implementation weaknesses; (2) we present their implementation and evaluation in a testbed based on the latest NFD version; and (3) we analyze their impact on the different ICN nodes (clients, access and core routers, content provider) composing a realistic topology. This work was published in IM 2017 conference [21].

Also, still in the context of the DOCTOR project, we refined our architecture to securely deploy NDN over NFV. Indeed, combining NFV fast service deployment and SDN fine grained control of data flows allows comprehensive network security monitoring. The DOCTOR architecture allows detecting, assessing and remediating attacks. NDN is an example of application made possible by SDN and NFV coexistence, since hardware implementation would be too expensive. We showed how NDN routers can be implemented and managed as VNFs. Security monitoring of the DOCTOR architecture is performed at two levels. First, host-level monitoring, provided by CyberCAPTOR, uses an attack graph approach based on network topology knowledge. It then suggests remediations to cut attack paths. We show how our monitoring tool integrates SDN and NFV specificities and how SDN and NFV make security monitoring more efficient. Then, application-level monitoring relies on the MMT probe. It monitors NDN-specific metrics from inside the VNFs and a central component can detect attack patterns corresponding to known flaws of the NDN protocol. These attacks are fed to the CyberCAPTOR module to integrate NDN attacks in attack graphs. This work was published in a book chapter "Guide to Security in SDN and NFV" from Springer's Computer Communications and Networks collection [35].

Finally, in cooperation with the University of Luxembourg, we have investigated interest flooding attacks in NDN. By nature, NDN communication assumes that requesting a content leads to emit an interest and forwarding it in the network until it reaches an appropriate content provider which then sends back data through the reverse path. Interest flooding attacks forge interests (requests) which cannot be satisfied by any data to be sent back to the emitter. As such, both the network and nodes are overloaded as the interests are flooded into the network and intermediate nodes have to store them locally in the pending interest table. We observed that most of literature mechanisms have been evaluated with very simple attack models. Actually, we had a great expertise in phishing attacks and social engineering that can be used to generate realistic phishing names for the NDN naming scheme. We thus create a new stealthy attack relying on natural language processing techniques to forge interests very similar to legitimate ones making inefficient all proposed counter-measures from the state-of-the-art [25].

7.2.3. Configuration security automation

Participants: Rémi Badonnel [contact], Abdelkader Lahmadi, Olivier Festor, Nicolas Schnepf, Maxime Compastié.

The main research challenge addressed in this work is focused on enabling configuration security automation in dynamic networks and services. In particular our objective is to support the efficient configuration and orchestration of security management operations.

The continuous growth and variety of networking significantly increases the complexity of management. It requires novel autonomic methods and techniques contributing to detection and prevention performances with respect to vulnerabilities and attacks.

We have pursued during Year 2017 the efforts on the orchestration of security functions in the context of mobile smart environments, with our joint work with Stephan Merz of the VeriDis project-team at Inria Nancy. We had already defined an automated verification technique, based on an extension of an SDN language, for checking both the control and the data planes related to security chains [24]. Complementarily, we proposed a strategy for generating SDN policies for protecting Android environments based on automata learning. Our solution collects traces of flow interactions of their applications, aggregates them in order to build finite-state models, and then infer SDN policy rules. We have designed and implemented aggregation and automata learning algorithms that allow precise and generic models of applications to be built. These models will be then used for configuring chains of security functions specified in the Pyretic language and verified with our Synaptic checker. We have developed a prototype of our solution implementing these algorithms, and evaluated its performances through a series of experiments based on the backend process miners Synoptic and Invarimint, in addition to our own algorithm. The experiments showed the benefits and limits of these methods in terms of simplicity, precision, genericity and expressivity, while varying the level of aggregation of the input flow traces.

In addition, we have worked on our software-defined security framework, for enabling the enforcement of security policies in distributed cloud environments. 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 [13]. In particular, we have investigated during Year 2017 the exploitability of unikernels to support our framework. Unikernels permit to build highly-constrained configurations limited to the strict necessary with a time-limited validity. We take benefits of their properties to reduce the attack exposure of cloud resources. We have formalized and integrated into our software-defined security framework, on-the-fly generation mechanisms of unikernel images that cope with security policy requirements. In that context, security mechanisms are directly integrated to the unikernel images at building time. A proof of concept prototype based on MirageOS was developed and the performance of such a software-based security strategy was evaluated through extensive series of experiments. We have also compared them to other regular virtualization solutions. Our results show that the costs induced by security mechanisms integration are relatively limited, and unikernels are well suited to minimize risk exposure.

7.3. Experimentation, Emulation, Reproducible Research

This section covers our work on experimentation on testbeds (mainly Grid'5000), on emulation (mainly around the Distem emulator), and on Reproducible Research.

7.3.1. Grid'5000 design and evolutions

Participants: Florent Didier, Arthur Garnier, Imed Maamria, Lucas Nussbaum [contact], Olivier Demengeon [SED], Teddy Valette [SED].

The team was again heavily involved in the evolutions and the governance of the Grid'5000 testbed.

7.3.1.1. Technical team management

Since the beginning of 2017, Lucas Nussbaum serves as the Grid'5000 *directeur technique* (CTO), managing the global technical team (9 FTE).

7.3.1.2. SILECS project

We are also heavily involved in the ongoing SILECS project, that aims at creating a new infrastructure on top of the foundations of Grid'5000 and FIT in order to meet the experimental research needs of the distributed computing and networking communities.

7.3.1.3. Promoting the testbed

In order to promote the testbed to the french devops and sysadmin community, we presented in [27] an overview of the testbed's capabilities.

7.3.1.4. Disk reservation

We contributed a new feature that will greatly help Big Data experimenters: the ability to reserve disks on nodes, in order to leave large datasets stored on nodes between nodes reservations.

7.3.1.5. Automated testing of the testbed

In order to ensure that all services remain functional, and that experimental results remain trustworthy and reproducible, we designed an infrastructure to automatically test the testbed and detect misconfigurations, regressions, uncontrolled hardware heterogeneity, etc. This work was described in [23] and later presented in [34].

7.3.1.6. Support for SDN experiments

We started the development of a tool to orchestrate SDN experiments on Grid'5000, combining KaVLAN and OpenVSwitch.

7.3.2. Emulation with Distem

Participants: Alexandre Merlin, Lucas Nussbaum [contact].

The ADT SDT project started in March. Initial work focused on improving the software developing infrastructure by adding automated regression tests on both correctness and performance. This should allow a new release in early 2018.

7.3.3. I/O access patterns analysis with eBPF

Participants: Abdulqawi Saif, Lucas Nussbaum [contact], Ye-Qiong Song.

In the context of Abdulqawi Saif's CIFRE PhD (with Xilopix), we explored the relevance of an emerging instrumentation technology for the Linux kernel, eBPF, and used it to analyze I/O access patterns of two popular NoSQL databases. A publication on this topic is expected in early 2018.

7.3.4. Performance study of public clouds

Participants: Souha Bel Haj Hassine, Lucas Nussbaum [contact].

We worked on clouds performance in the context of an ongoing collaboration with *CloudScreener*, a French startup founded in 2012 that has developed tools for cloud price and performance benchmarks and automated cloud recommendation to optimize the decision making process in the context of cloud computing. We designed methods and tools to do performance evaluation of public clouds focusing on (1) outlining performance variability over time; (2) identifying adverse strategies that might be deployed by cloud providers in order to vary the performance level over time.

7.3.4.1. Testbeds federation and collaborations in the testbeds community

The Fed4FIRE+ H2020 project started in January 2017 and will run until the end of September 2021. This project aims at consolidating the federation of testbeds in Europe of which Grid'500 is a member.

We are also active in the GEFI initiative that aims at building links between the US testbeds community (GENI) and their european (FIRE), japanese and brazilian counterparts. We participated in the annual GEFI meeting where gave two talks [33][34] and chaired the session on reproducibility.

7.3.4.2. Experimentation and reproducible research

In addition to the work already mentioned on testbed testing [23], [34], we worked on a survey of testbeds and their features for reproducible research [22]. We also gave several talks on reproducible research and testbeds at *École ARCHI* [5], *École RESCOM* [6], and Inria webinars on Reproducible Research [7].

7.4. Routing

7.4.1. NDN routing

Participants: Isabelle Chrisment [contact], Thomas Silverston, Elian Aubry.

As NDN relies on content names instead of host address it cannot rely on traditional Internet routing. Therefore it is essential to propose a routing scheme adapted for NDN. In [8] we have presented SRSC, our SDN-based Routing Scheme for CCN/NDN and its implementation. SRSC relies on the SDN paradigm. A controller is responsible to forward decisions and to set up rules into NDN nodes. So we have implemented SRSC into NDNx. We have deployed an NDN testbed within a virtual environment emulating a real ISP topology in order to evaluate the performances of our proposal with real-world experiments. We have demonstrated the feasibility of SRSC and its ability to forward Interest messages in a fully deployed NDN environment while keeping low overhead and computation time and high caching performances.

7.4.2. Energy-Aware and QoS Routing for Wireless Sensor Networks

Participants: Evangelia Tsiontsiou, Bernardetta Addis, Ye-Qiong Song [contact].

The main research problems in the domain of routing data packets in a multi-hop wireless sensor network are the optimisation of the energy and the routing under multi-criteria QoS constraints (e.g., energy, reliability, delay, ...). To address these problems, we proposed, in the PhD thesis of E. Tiontsiou, two contributions. The first contribution is an optimal probabilistic energy-aware routing protocol, allowing to energy usage balancing. Comparing to the existing probabilistic routing protocols, our solution is based on the computation of the optimal probabilities by solving a linear programming problem. Our second contribution is an operator calculus algebra based multi-constrained routing protocol. It is fundamentally different from the existing solutions since it can simultaneously consider several constraints, instead of their combination.

7.5. Smart*: design, multi-modeling and co-simulation and supervision of mobile CPS/IoT

Participants: Laurent Ciarletta [contact], Ye-Qiong Song, Yannick Presse, Julien Vaubourg, Emmanuel Nataf, Petro Aksonenko, Virgile Dauge, Louis Viard, Florian Greff, Virginie Galtier, Thomas Paris.

Vincent Chevrier (former Maia team, Dep 5, LORIA) is a collaborator and the correspondant for the MS4SG/MECSYCO project, as well as Christine Bourjot (former MAIA team, Dep 5, LORIA).

Sylvain Contassot-Vivier (Dep 3, Loria) is a collaborator on the Grone project and is directing Virgile Daugé with Laurent Ciarletta.

Pierre-Etienne Moreau is a collaborator on the CEOS project and is directing Louis Viard with Laurent Ciarletta.

Virginie Galtier from CentraleSupélec is now a member of the Loria laboratory and will integrate the future Simbiot team (Systems of Interactive aMBient Intelligent ObjecTs).

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 in 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 [45] 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) project 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. We also collaborated with researchers from the Green UL laboratory.

In 2017 we worked on the following research topics:

- Overall assessment and evaluation of complex systems.
- Cyber Physical Systems and Smart *.

  We have continued the design and implementation of the Aetournos platform at Loria which will be part of the Creativ'Lab. The collective movements of a flock of flying communicating robots / UAVs, evolving in potentially perturbed environment constitutes a good example of a Cyber Physical System. Several projects have started during the last part of 2017. One of the emerging topic in this area is the safety of Mobile IoT/CPS with regards to their environment and users.

  – The Grone (Interreg) project involves partners from the 4 countries of the Grande Région (Centrale Supélec, LIST, Univ Luxembourg, Univ Liège, Fraunhofer IZFP to name a few). The main goal is to develop UAV based solution for the surveillance of industrial and agricultural sites and the exploration of GPS denied and underground environments. A PhD has been started in March 2017 (Systèmes cyber-physiques autonomes et communicants en milieux hostiles. Application à l'exploration par robots mobiles. Virgile Daugé).

  – and the CEOS (FUI22) project involving high profile companies (Thales C&S, EDF R&D, ENEDIS and Aéroport de Lyon) as well as academic partners (AOSTE2 Inria, ESIEE) and collaborating SMEs (RT@W, ADCIS, Alerion). This project focuses on the safety of UAV based monitoring solutions for OIV (Opérateurs d'Intéret Vital) infrastructures. A PhD has been started in November 2017 (Environnement de développement et d'analyse de propriétés pour des systèmes cyber-physiques mobiles. Louis Viard).

  The work on Software Defined Real-Time Mesh networks (Florian Greff's PhD CIFRE with Thales R&T) has given many results as he plans to defend his work in march 2018 [15], [39], [14].

On more specific subject of innovative sensors for mobile and interactive IoT, a collaborative project with the KPI (Ukraine) university has been started with a projected PhD (Méthodes optimisées de calibration, d'alignement et algorithmes d'attitude avancés pour les systèmes de navigation inertiels fixés, Petro Aksonenko). Several papers have been published [9] [44] in 2017.

- (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 which led us to the Starburst Computing SATT projects in 2016 and 2017. A spin off has been founded in 2017 that is getting the licences for the resulting IP (the software is under the APP process at the time of this writing). Starburst is already involved in a AMI project with the Globlinz game studio and the lab and has officially been accepted in novembre 2017 and will be operational in 2018.
- Smart *: MS4SG / MECSYCO-NG has given us the opportunity to link simulations tools with a strong focus on FMI (Functional Mockup Interface) and network simulators (NS3/Omnet++). 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 constant improvements in 2017 thanks to the ressources provided by the MECSYCO-NG project in collaboration with EDF R&D (http://www.mecsyco.com), and the work of Thomas Paris and Julien Vaubourg.

  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.

The technical report [43] has been extended into a journal paper under revision for a publication in 2018.

7.6. Quality-of-Service

7.6.1. *Self-adaptive MAC protocol for both QoS and energy efficiency in IoT*

Participants: Shuguo Zhuo, François Despaux, Ye-Qiong Song [contact].

The diversity of IoT applications implies the requirement of reliable yet efficient MAC solutions for supporting transmissions for various traffic patterns. We have mainly contributed to enhance the implementation of the high efficient traffic self-adaptive MAC protocols. As part of RIOT ADT project, our main achievements are the development of two MAC protocols lw-MAC and GoMacH [26]. lw-MAC is similar to X-MAC and ContikiMAC. It allows to introduce a first duty-cycled MAC into RIOT IoT protocol stack. GoMacH is a nearly optimal protocol that provides high reliability and throughput for handling various traffic loads in IoT. GoMacH seamlessly integrates several outstanding techniques. It adopts the phase-lock scheme to achieve low-power duty-cycled communication. It also utilizes a dynamic slots allocation scheme for providing accurate and instantaneous throughput boost. Furthermore, like in TSCH, GoMacH spreads its communications onto IEEE 802.15.4's 16 channels, leading to high reliability. GoMacH has been implemented in open source on RIOT OS, and has also been seamlessly integrated into IETF's 6LoWPAN/RPL/UDP stack as well as CCN-light. Experimental results on SAMR21-xpro test-beds and IoT-LAB verify the practicality of GoMacH and its capabilities for consistently providing high throughput, high delivery ratio, and low radio duty-cycle. They are both publically available on the RIOT open source github.

7.6.2. *QoS and fault-tolerance in distributed real-time systems*

Participants: Florian Greff, Laurent Ciarletta, Arnauld Samama [Thales TRT], Dorin Maxim, 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 have developed a Software-Defined Real-time Network (SDRN) framework [14]. SDRN deals with the real-time flow allocation problem in mesh networks. The objective is to find a suitable path under delay constraint while allowing load balancing. For this purpose, combined online flow admission control and pathfinding algorithms have been developed on an SDN-like controller. At switch level, each output port is ruled by a credit-based weighted round robin, allowing isolation of flows. As a consequence, a freshly admitted flow will not influence existing flows, allowing incremental online admission of new flows. This approach has been applied to a RapidIO mesh network example and compared with the compositional performance analysis method. Numerical results clearly show the benefit of our proposal in terms of complexity and delay bound pessimism. In [15], Fault-tolerance issue in mesh networks has been addressed. In fact, one of the major advantages of a mesh topology is its ability to leverage the path redundancy in order to recover from link or node failures, through a flow reconfiguration process. However, one needs to ensure that hard real-time packets will keep being delivered on time during this transient reconfiguration period. Anticipating each possible fault is very complex and can result in a waste of network resource. Our contribution is the combination of an optimized content-centric source routing in nominal mode and a destination-tag flexible and scalable routing in transient recovery mode. We show the benefit of this approach in terms of flexibility and network resource utilization. Our method can ensure real-time properties enforcement even during the transient reconfiguration period. Algorithms have been developed to extend the SDRN flow allocation and routing methods in order to implement this hybrid fault-tolerant extension.

As part of Eurostars RETINA project, in the in-vehicle networking domain, we have focused on the evaluation of the worst-case response time of AVB traffic under time-aware shaper of TSN (time-sensitive networking). It is a hierarchical real-time scheduling problem, where a packet is scheduled by the credit-based shaper, priority and time-aware shaper (TDMA). We have proved that the eligible interval approach, developed for AVB, is still hold for TSN case. The worst case delay expression, as well as the feasibility condition are deduced. Our methods (analysis and simulation) are applied to an automotive use case, which is defined within the Eurostars RETINA project, and where both control data traffic and AVB traffic must be guaranteed. It has been shown that our delay bound is tight in single switch case [19].

8. Bilateral Contracts and Grants with Industry

8.1. 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)

8.2. 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, Thales (Palaiseau, France):
  - CIFRE PhD (Pierre-Olivier Brissaud, supervised by Isabelle Chrisment and Jérôme François)
  - Anomaly detection in encrypted network traffic
- 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-Defined 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, Cynapsys Technologies (Paris, France):
  - CIFRE PhD (Haftay Gebreslasie Abreha, supervised by Michael Rusinowitch, Adel Bouhoula and Abdelkader Lahmadi)
  - Compressed and Verifiable Filtering Rules in Software-defined Networking

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. 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) and has been successfully defended in october 2017.

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 [10] and [31]).

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

9.1.2. Hydradrone FEDER Région Lorraine project

Participants: 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, a spinoff from Loria/UL.

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, provides the use cases and terrain (and business) validation, while Alerion is working on the integration and engineering of the solution.

This third year has been dedicated to the development of the surface controller for the Hydradrones along with the development of a new small version, and the integration of environmental sensors. The project has been extended towards the summer 2018 in order to finish the integration and tests.

9.1.3. Satelor AME Lorraine regional project

Participants: François Despaux, 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 achieved. 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 realized at one EHPAD including several rooms. The second topic is related to improve 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). The third topic is UWB-based indoor localization and its use for tracking and detecting falls of the elderlies. Experiments have shown a great benefice of multi-sensor fusion (e.g. localization + accelerometer) for increasing the detection accuracy.

9.2. National Initiatives

9.2.1. ANR

9.2.1.1. ANR BottleNet

Participants: Isabelle Chrisment [contact], Thibault Cholez, Vassili Rivron.

The Quality of Experience (QoE) when accessing the Internet, on which more and more human activities depend on, 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 in 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 them 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.

9.2.1.2. ANR Doctor

Participants: Thibault Cholez [contact], Xavier Marchal, 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 plus one year of extension (2018) to align the scientific production with the budget consumption. 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.

This year, we focused on the second workpackage dedicated to security. We did a joint work with UTT investigating the impact on the Content Poisoning Attack on the NDN architecture [21]. We also wrote a book chapter about our use of NDN and NFV technologies to deploy an NDN network while providing advanced monitoring and security functions [35].

We also improved our HTTP/NDN gateway that will be soon released for the community and which design and evaluation will be submitted in a journal.

The next (and last) year of the project will be dedicated to the orchestration of our virtualized NDN architecture to manage its performance and security, and to the deployment of a testbed carrying real user traffic.

9.2.1.3. FUI HUMA (01/09/2015-31/08/2018)

Participants: Giulia de Santis, Soline Blanc, Sofiane Lagraa, 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 last for several months 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 2017, our contribution focused on defining a graph-mining technique to discover dependencies among security events clustering techniques in order to group individual events into a common one. We applied our technique to darknet data as shown in section 7.2.1. 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 (7.2.1). We also technically contribute to the definition of APT scenarios by providing a very stealthy scanning approach (Wiscan described in 7.1.2). 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.

9.2.1.4. 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. We have specified a management framework dedicated to cloud software-defined security. It relies on on-the-fly generation and execution of unikernels in order to build highly-constrained configurations. The solution has been evaluated through extensive series of experiments, based on a proof-of-concept prototype using MirageOS. Results show that the costs induced by security mechanisms integration are relatively limited, and unikernels are well suited to minimize risk exposure.

9.2.1.5. 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, 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, whose first session will open end of 2018, covers the fundamental concepts, architectures and protocols of the domain, as well as their evolution in the context of future Internet, and includes practical labs and exercises using widely-used tools and technologies.

9.2.2. Technological Development Action (ADT)

9.2.2.1. ADT UASS

The goal of this ADT provides 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 tutored 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.

9.2.2.2. ADT VERTEX

This ADT started in 2016 and will end on 2018. The Madynes project is a major partner funded at the level of 120k€. ADT VERTEX built 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. Previously developed prototypes are also being consolidated, and the necessary improvements to user management and tracking are also being performed.

9.2.2.3. ADT SDT

Built on the Distem emulator, that enables the creation of virtual experimental environments from clusters of homogeneous machines, this project aims at enlarging the scope of use of Distem to additional fields: *Software Defined Networking*, *Named Data Networking*, *Big Data*. In addition, we will explore *temporal dilation* as a technique to study future infrastructures.

The project started in 2017 and will end in 2019.

9.2.2.4. 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. Based on these generic functions, we have developed two duty-cycled MAC protocols lw-MAC and GoMacH which are above IEEE802.15.4. lw-MAC is a single channel MAC protocol that has similar principle of X-MAC and ContikiMAC. GoMacH [26] is a traffic-adaptive multi-channel MAC protocol for IoT which exhibes low power consumption and high throughput performance. Both are integrated into the RIOT IoT protocol stack and merged into RIOT master branch. They are publically available in RIOT open source github.

9.2.2.5. ATT AMICS

The ATT AMICS is run in cooperation with the High Security Lab (HSL). The goal is to develop a customizable security analytics stack as a service. The added value of the HSL is to cross-correlate customer data with Internet probes hosted at HSL collecting tons of security data. Indeed, the basic service provided to potential customer is a VPN on top of which custom modules can be added. In 2017, we setup the VPN elements and also developed a flexible framework for security analysis. Different moddules have already been defined and implemented: blacklists aggregators to gather continuously information from third parties providing blacklists, real-time verification of traffic going through the VPN using blacklists, real-time detection of IP spoofing by correlating user traffic with HSL darknet traffic and real-time detection of customer hosts infected by a malware.

9.2.3. Inria Project Lab

9.2.3.1. IPL BetterNet

Participants: Isabelle Chrisment [contact], Thibault Cholez, Vassili Rivron, Lakhdar Meftah [University of Lille].

The Inria Project Lab BetterNet (https://project.inria.fr/betternet) has been 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 this IPL and in particular Isabelle Chrisment who coordinates the project.

In 2017, the main activities of the project focused on federating Inria's monitoring tools (APISENSE, Fathom, Hostview, ACQUA) and building our open measurement platform for acquiring data.

Lakhdar Meftah, a shared PhD student with the SPIRALS team (Inria/University of Lille) has worked on a privacy preservation scheme using data dissemination that introduces an a priori data anonymization and improves user privacy without compromising the overall quality of the crowdsourced dataset.

9.2.3.2. IPL Discovery

Participant: Lucas Nussbaum [contact].

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

The DISCOVERY initiative aims at exploring a new way of operating Utility Computing (UC) resources by leveraging any facilities available through the Internet in order to deliver widely distributed platforms that can better match the geographical dispersal of users as well as the ever increasing demand. Critical to the emergence of such locality-based UC (also referred as Fog/Edge Computing) platforms is the availability of appropriate operating mechanisms. The main objective of DISCOVERY is to design, implement, demonstrate and promote a new kind of Cloud Operating System (OS) that will enable the management of such a large-scale and widely distributed infrastructure in an unified and friendly manner.

The consortium is composed of experts in the following research areas: large-scale infrastructure management systems, networking and P2P algorithms. Moreover, two key network operators, namely Orange and RENATER, are involved in the project.

By deploying and using a Fog/Edge OS on backbones, our ultimate vision is to enable large parts of the Internet to be hosted and operated by its internal structure itself: a scalable set of resources delivered by any computing facilities forming the Internet, starting from the larger hubs operated by ISPs, governments and academic institutions, to any idle resources that may be provided by end users.

MADYNES contributes to the DISCOVERY IPL on the networking axis. A CIFRE PhD with Orange is expected to start at the beginning of 2018.

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

9.3.1.1. Fed4Fire+ (2017-2022)

Title: Federation for FIRE Plus

Program: H2020

Duration: January 2017 - December 2021

Coordinator: Interuniversitair Micro-Electronicacentrum Imec VZW

Partners:

Universidad de Malaga

National Technical University of Athens - NTUA

The Provost, Fellows, Foundation Scholars & the other members of board of the College of the Holy & Undivided Trinity of Queen Elizabeth Near Dublin

Ethniko Kentro Erevnas Kai Technologikis Anaptyxis

GEANT LImited

Institut Jozef Stefan

Mandat International Alias Fondation Pour la Cooperation Internationale

Universite Pierre et Marie Curie - Paris 6

Universidad De Cantabria

Fundacio Privada I2CAT, Internet I Innovacio Digital A Catalunya

EURESCOM-European Institute For Research And Strategic Studies in Telecommunications GMBH

Nordunet A/S

Technische Universitaet Berlin

Instytut Chemii Bioorganicznej Polskiej Akademii Nauk

Fraunhofer Gesellschaft zur Foerderung Der Angewandten Forschung E.V.

Universiteit Van Amsterdam

University of Southampton

Martel GMBH

Atos Spain SA

Institut National de Recherche en Informatique et automatique

Inria contact: David Margery (for MADYNES: Lucas Nussbaum)

Fed4FIRE+ is a successor project to Fed4FIRE. In Fed4FIRE+, we more directly integrate Grid'5000 into the wider eco-system of experimental platforms in Europe and beyond using results we developped in Fed4FIRE. We will also provide a generalised proxy mechanisms to allow users with Fed4FIRE identities to interact with services giving access to different testbeds but not designed to support Fed4FIRE identities. Finally, we will work on orchestration of experiments in a federation context. Fed4FIRE+ was prepared in 2016, and has started January 1st, 2017.

9.3.2. Collaborations in European Programs, Except FP7 & H2020

9.3.2.1. 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.

9.4. International Initiatives

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

9.4.1.1. IoT4D

Title: Internet of Things for Developping countries

International Partner (Institution - Laboratory - Researcher):

UY (Cameroon) - MASECNeSS - Thomas DJOTIO NDIE

Start year: 2016

See also: https://team.inria.fr/iot4dc/

Our goal is to connect wireless sensors networks (WSN) to the Internet through gateways. WSN should have several accessible 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 a peculiar context featuring unreliable communications and equipments that are easily disturbed by environment .

9.4.1.2. 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

Joint publications: [25], [12], [16]

Start year: 2016

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

Networking is deeply evolving with the advent of new paradigms making the network more configurable and more dynamic. In particular, SDN (Software-Defined Network) consists in splitting the control plane and the data plane. A SDN-enabled switch is so only viewed as a specialized device in forwarding data traffic while a logically centralized controller exposes interfaces to services and applications strengthening their coupling. Hence, network is not only a medium of communication but a software component. In the same context, NFV (Network Function Virtualization) promotes the virtualization of all kinds of network functions (router, load-balancer, firewall. . .) on commodity server, a server in a cloud. These technologies are deeply changing networking principle by allowing a high flexibility in network management. The new features provided by these concepts will thus allow to reinvent the network management in all its areas, especially for network monitoring and provisioning. In addition, even more recent propositions argue for a finer granularity applying the programmability idea of SDN (working at flow level) to packet processing level by promoting the definition of a common language like P4 to reconfigure any switch at low level (vendor independent). The original goal of the associate team is to explore co-jointly this research area through four directions: Monitoring of NFV- and SDN-enabled networks, investigating the integration of data analytics as virtualized functions in virtual networks, security of SDN networks, service chain composition, programming packet processing with P4 and other equivalents. ICN (Information Centric Networking) is also an important topic which is addressed in the team, especially regarding performance (with SDN) and security.

Furthermore, management of blockchain has been set as a new research topic to be focused in the team at the end of 2016. In the scope of network management, our objective is to design monitoring and orchestration methods for blockchain. In particular, we want to assess the relationships and impact between blockchain and network performance. We will have to define proper metrics to catch meaningful data to be analyzed. Moreover, a blockchain technology is by nature without authority (except in the private case), configuration requires thus to enforce some collaboration between nodes.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. Member of the Organizing Committees

Rémi Badonnel: IEEE/IFIP International Symposium on Integrated Network Management (IEEE/IFIP IM 2017), IFIP International Conference on Autonomous Infrastructure, Management and Security (IFIP AIMS 2017), IEEE/IFIP International Network Operations and Management Symposium (IEEE/IFIP NOMS 2018).

Lucas Nussbaum: 4th International Workshop on Reproducibility in Parallel Computing (REPPAR 2017).

10.1.2. Scientific Events Selection

10.1.2.1. Chair of Conference Program Committees

Isabelle Chrisment was a TPC co-chair of the 2nd IEEE/IFIP Workshop on Analytics for Network and Service Management (AnNet 2017). She was member of the steering committee for RESSI'17 (Rendez-vous de la Recherche et de l'Enseignement de la Sécurité des Systèmes d'Information).

Rémi Badonnel is a TPC co-chair for the Third IEEE/IFIP International Workshop on Analytics for Network and Service Management (AnNet 2018).

Jérôme François was a co-chair of the 3rd IEEE/IFIP Workshop on Security for Emerging Distributed Network Technologies (DISSECT).

Lucas nussbaum was a co-chair of the *High Performance Computing in/with the Cloud* track at 9th IEEE International Conference on Cloud Computing Technology and Science (CloudCom 2017).

10.1.2.2. Member of the Conference Program Committees

Rémi Badonnel: IFIP/IEEE International Conference on Network and Service Management (IFIP/IEEE CNSM 2017) ; IEEE Conference on Network Softwarization (IEEE NetSoft 2017) ; IFIP/IEEE International Symposium on Integrated Network Management (IFIP/IEEE IM 2017) ; IFIP International Conference on Autonomous Infrastructure, Management and Security (IFIP AIMS 2017) ; IEEE Global Information Infrastructure and Networking Symposium (IEEE GIIS 2017) ; Asia-Pacific Network Operations and Management Symposium (APNOMS 2017) ; IEEE International Conference on Communications (IEEE ICC - SAC 2017).

Olivier Festor: IFIP/IEEE International Conference on Network and Service Management (IFIP/IEEE CNSM 2017) ; IEEE Conference on Network Softwarization (IEEE NetSoft 2017) ; IFIP/IEEE International Symposium on Integrated Network Management (IFIP/IEEE IM 2017) ; IFIP International Conference on Autonomous Infrastructure, Management and Security (IFIP AIMS 2017) ; IFIP Networking 2017.

Abdelkader Lahmadi: IEEE Conference on Network Softwarization (IEEE NetSoft 2017) ; IFIP/IEEE International Symposium on Integrated Network Management (IFIP/IEEE IM 2017) ; Asia-Pacific Network Operations and Management Symposium (APNOMS 2017) ; 1st Cyber Security in Networking Conference (CSNET 2017).

Jérôme François: IEEE Conference on Network Softwarization (IEEE NetSoft 2017) ; IFIP/IEEE International Symposium on Integrated Network Management (IFIP/IEEE IM 2017) ; Asia-Pacific Network Operations and Management Symposium (APNOMS 2017) ; IEEE Global Information Infrastructure and Networking Symposium (IEEE GIIS 2017) ; Principles, Systems and Applications of IP Telecommunications (IPTComm'17); IFIP/IEEE International Workshop on Management of SDN and NFV Systems (IFIP/IEEE ManSDN 2017).

Thibault Cholez: IEEE/IFIP Workshop on Security for Emerging Distributed Network Technologies (DISSECT 2017); 4th ACM Conference on Information-Centric Networking: Demos and Posters tracks (ICN 2017).

Lucas Nussbaum: 4th International Workshop on Computer and Networking Experimental Research Using Testbeds (CNERT'2017) ; 26th IEEE International Conference on Enabling Technologies: Infrastructure for Collaborative Enterprises (WETICE'2017) ; 23nd IEEE International Conference on Parallel and Distributed Systems (ICPADS'2017).

Isabelle Chrisment: IFIP International Conference on Autonomous Infrastructures, Management and Security (IFIP AIMS'17) ; Rencontres Francophones sur la Conception de Protocoles, l'évaluation de Performance et l'Expérimentation Aspects Algorithmiques de Télécommunications (CoResl'17) ; IEEE/IFIP International Symposium on Network Operations and Management (IFIP/IEEE IM'17).

Ye-Qiong Song: IEEE International Workshop on Factory Communication Systems (WFCS 2017); IEEE International Conference on Communications and Networking (ComNet 2017) ; IEEE International Conference on Emerging Technologies and Factory Automation (ETFA 2017) ; 25th International Conference on Real-Time Networks and Systems (RTNS 2017) ; IEEE Clobecom 2017; ICOST 2017; IEEE RTCSA 2017.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

Rémi Badonnel is Associate Editor for the Wiley International Journal of Network Management (IJNM), and serves as a Guest Editor for a Special Issue on Management of SDN/NFV-based Systems in the same journal.

Jérôme François serves as a Guest Editor for a Special Issue on Security for Emerging Open Networking Technologies in Wiley International Journal of Network Management (IJNM).

Ye-Qiong Song is an Associate Editor for the Elsevier Computers and Electrical Engineering journal, and for the Journal of Multimedia Information System.

10.1.3.2. 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), Elsevier Journal on Computer Communications (COMCOM), Elsevier Journal on Communication Networks (COMNET), Elsevier Journal on Computers and Security (COSE).

Olivier Ferstor: Elsevier Computers & Security.

Abdelkader Lahmadi: 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), International Journal of Distributed Sensor Networks (IJDSN), IEEE Communications Magazine (COMMAG).

Jérôme François: IEEE Communications Magazine (COMMAG), Wiley International Journal of Network Management (IJNM).

Thibault Cholez: Wiley International Journal of Network Management (IJNM), Elsevier Journal on Communication Networks (COMNET).

Lucas Nussbaum: PLOS ONE ; Springer Journal of Internet Services and Applications (JISA) ; International Journal of Grid and Utility Computing (IJGUC) ; IEEE Transactions on Services Computing (TSC).

Isabelle Chrisment: IEEE Transactions on Network and Service Management (IEEE TNSM), IEEE Communications Magazine (COMMAG). Elsevier Journal Computer Communications (COMCOM)

Ye-Qiong Song: Elsevier Computers and Electrical Engineering journal, IEEE Transactions on Industrial Informatics, IEEE Communications surveys and tutorials.

10.1.4. Invited Talks

Jérôme François:

- IRTF NMRG (IETF 100), Singapore: "Network traffic analysis for encrypted traffic and security monitoring"
- 7th annual Inria@SiliconValley workshop, Berkeley, CA, USA: panelist on "Blockchain Technology for Cybersecurity and Social Impact" and presenter in session "Scaling up for IoT"
- Annual CODE event of the Universität der Bundeswehr, Munich, Germany: panelist on "Smart Atttacks requires smart defence"

Lucas Nussbaum:

- École ARCHI 2017: "Experimenting on Architectures for High Performance Computing"
- Reproducible Research Webinars: "Testbeds in Computer Science"
- École RESCOM 2017: "Scaling Your Experiments"

Vassili Rivron:

- CERReV/Université de Caen Normandie Conference on *Les services gratuits du web entre empowerment et hégémonie : contradictions et régulations de l'économie collaborative*, "Sites d'information et bloqueurs de publicité : intermédiaires de l'auto-régulation publicitaires dans le champ journalistique", March 2017.
- SHS Seminar in Loria, "News-sites and adblockers : intermediaries of advertising self-regulation in the field of journalism", in collaboration with Thibault Cholez, June 2017.

10.1.5. Scientific Expertise

Abdelkader Lahmadi served as a member of the Selection Committee of the 2017 ComSoc Student Competition "Communications Technology Changing the World".

Jérôme François serves as reviewer for ANRT to evaluate a CIFRE PhD proposition and as reviewer for ANR.

Yeqiong Song serves as reviewer for ANRT to evaluate a CIFRE PhD proposition and as reviewer for ANR.

10.1.6. Research Administration

Abdelkader Lahmadi is a member of the CDT of Inria Nancy Grand Est.

Jérôme François is a member of the Horizon Startup local committee in Nancy Grand Est.

Isabelle Chrisment is a member of :

- AFNIC's scientific council
- scientific pole AM2I (Automatique, Mathématiques, Informatique et leurs Interaction) at Université de Lorraine
- COMIPERS at Inria Nancy Grand Est.
- CMI (Commission de la Mention Informatique), part of the doctoral school IAEM.

She also served as a member of the working group "Plan Stratégique Scientifique Inria".

Olivier Festor is member of the Scientific Council of Telecom Sud Paris. Olivier Festor is leading the IFIP TC6 Working Group 6.6 : Network and Service Management. He is also in charge of the CERI initiative between France and Germany.

Yeqiong Song is head of Department 3 of LORIA.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Olivier Festor is the Director of the TELECOM Nancy Engineering School.

Rémi Badonnel is heading the Internet Systems and Security 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 school.

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).

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

Abdelkader Lahmadi 280 hours - L3, M1, M2 - Real time and Embedded Systems Programming, Distributed Systems and Algorithms, Green IT, Algorithms and Advanced Programming - ENSEM Engineering School

Yeqiong Song 200 hours - L3, M1, M2 - Green IT, Algorithms and Advanced Programming, Databases networking - ENSEM Engineering School

Jérôme François 70 hours - M1, M2 -Network security, Big Data - TELECOM Nancy, Université de Lorraine, University of Lorraine

Thibault Cholez 300 hours - L3, M1, M2 - Techniques and Tools for Programming, Computer Networks, Object-Oriented Programming, Network Services, Constraint development on small Connected Objects, Mobile applications and Internet of Things, Project Management - TELECOM Nancy, Université de Lorraine, University of Lorraine

Isabelle Chrisment 220 hours -L3, M1, M2 -C and Shell Programming, Computer Networking, Operating Systems, Network Security. - TELECOM Nancy, Université de Lorraine

E-learning

MOOC: Thibault Cholez, Supervision de réseaux et services (concept clés avec SNMP), 1 semaine (5 leçons), FUN, Université de Lorraine, Ingénieur, formation initiale et continue, ouverture en janvier 2018.

MOOC: Rémi Badonnel, Laurent Andrey, Supervision de réseaux et services (monitoring avec Nagios), 1 semaine (5 leçons), FUN, Université de Lorraine, Ingénieur, formation initiale et continue, ouverture en janvier 2018.

MOOC: Olivier Festor, Abdelkader Lahmadi, Supervision de réseaux et services (instrumentation avec JMX), 1 semaine (3 leçons), FUN, Université de Lorraine, Ingénieur, formation initiale et continue, ouverture en janvier 2018.

MOOC: Jérôme François, Supervision de réseaux et services (évolution des protocoles), 1 semaine (4 leçons), FUN, Université de Lorraine, Ingénieur, formation initiale et continue, ouverture en janvier 2018.

10.2.2. Supervision

PhD: Wazen Shbair, *Service-Level Monitoring of HTTPS Traffic* [1] defended on May 3rd 2017, University of Lorraine, supervised by Isabelle Chrisment and Thibault Cholez.

PhD: Julien Vaubourg, *Intégration de modèles de réseaux IP à un multi-modèle DEVS, pour la co-simulation de systèmes cyber-physiques* [2], defended in April 2017, Université de Lorraine, supervised by Vincent Chevrier and Laurent Ciarletta.

PhD: Evangelia Tsiontsiou, *Multi-constrained QoS Routing and Energy Optimization in Wireless Sensor Networks*, defended on December 15th 2017, University of Lorraine, supervised by Ye-Qiong Song and Bernardetta Addis.

PhD: Patrick-Olivier Kamgueu, *Configuration Dynamique et Routage pour l'Internet des Objets*, defended on December 18th 2017, Université de Yaoundé & Universiité de Lorrain, supervised by Olivier Festor, Emmanuel Nataf and Thomas Djotio

PhD: Elian Aubry, *Protocole de routage pour l'architecture NDN*, defended on December 19th 2017, University of Lorraine, supervised by Isabelle Chrisment and Thomas Silverston

PhD in progress: Thomas Paris, *Mo, délisation de systèmes complexes par composition*, since September 2015, supervised by Vincent Chevrier and Laurent Ciarletta.

PhD in progress: Maxime Compastie, *Software-Defined Security for the Cloud*, since December 2015, supervised by Olivier Festor and Rémi Badonnel.

PhD in progress: Florian Greff, *QoS and fault-tolerance of distributed real-time systems over mesh networks*, since Feb. 2015, supervised by Ye-Qiong Song and Laurent Ciarletta.

PhD in progress: Nicolas Schnepf, *Orchestration and Verification of Security Functions for Smart Environments*, since October 2016, supervised by Stephan Merz, Rémi Badonnel and Abdelkader Lahmadi.

PhD in progress: Giulia De Santis, *Data Analytics for Security*, since October 2015, supervised by Olivier Festor, Abdelkader Lahmadi and Jérôme François.

PhD in progress: Paul Chaignon, *Mécanismes de supervision de la sécurité dans un réseau programmable de type SDN/NFV*, since November 2015, supervised by Olivier Festor, Kahina Lazri and Jérôme François.

PhD in progress: Xavier Marchal, *Secure operation of virtualized Named Data Networks*, since December 2015, supervised by Olivier Festor and Thibault Cholez.

PhD in progress: Salvatore Signorello, *A multifold approach to address the security issues of stateful forwarding mechanisms in Information- Centric Networks*, since December 2014, supervised by Olivier Festor, Jérôme François and Radu State.

PhD in progress: Abdulqawi Saif, *Open Science for the scalability of a new generation search technology*, since December 2015, supervised by Ye-Qiong Song and Lucas Nussbaum.

PhD in progress: Pierre-Olivier Brissaud, *Anomaly detection in encrypted traffic*, since July 2016, supervised by Isabelle Chrisment, Jérôme François and Thibault Cholez.

PhD in progress: Petro Aksonenko, *Positionnement robuste pour véhicules autonomes à base de fusion de données de capteurs reposant sur les systèmes de navigation inertielle*, since October 2016, supervised by Patrick Henaff (Biscuit, Dep 5, loria), Vadim Avrutov (Kiev Polytechnic institute in Urkaine) and Laurent Ciarletta.

PhD in progress: Lakhdar Meftah, *Cartography of the quality of experience for mobile internet access*, since November 2016, supervised by Romain Rouvoy and Isabelle Chrisment.

PhD in progress: Haftay Gebreslasie Abreha, *Compressed and Verifiable Filtering Rules in Software-defined Networking*, since Octobrer 2017, supervised by Michael Rusinowitch, Abdelkader Lahmadi and Adel Bouhoula.

PhD in progress: Mingxiao Ma, *Cyber-physical systems defense through smart network configuration*, since December 2017, supervised by Isabelle Chrisment and Abdelkader Lahmadi.

PhD in progress: Louis Viard, *Environnement de développement et d'analyse de propriétés pour des systèmes cyber-physiques mobiles*, since November 2017, supervised by Pierre-Etienne Moreau and Laurent Ciarletta.

10.2.3. Juries

Team members participated to the following Ph.D. defense committees in:

- Maryam Barshan, PhD in Computer Science from Ghent University, Belgium. Title: Cloud Resource Provisioning and Bandwidth Management in Media-Centric Networks, August 2017 – (Rémi Badonnel as reviewer).
- Jose Jair Cardoso de Santanna, PhD in Computer Science from University of Twente, The Netehrlands. Title: DDOS-as-a-Service - Investigating Booter Websites, November 2017 – (Olivier Festor as reviewer).
- Amina Boubendir, PhD in Computer Science from TELECOM ParisTech, France. Title: Flexibility and Dynamicity for Open Network-as-a-Service : From Architecture Modeling to Deployment, March 2017 – (Olivier Festor as reviewer).
- Merve Sahin, PhD in Computer Science from TELECOM ParisTech, France. Title: Understanding Telephony Fraud as an Essential Step to Better Fight It, September 2017 – (Olivier Festor as reviewer).
- Christian Hammerschmidt, PhD in Computer Science from the University of Luxembourg, Luxembourg Title: Learning Finite Automata via Flexible State-Merging and Applications in Networking – (Jérôme François as reviewer).
- Pascal Thubert, PhD in Computer Science from IMT Atlantique - Bretagne -Pays de Loire, France. Title: Converging over Deterministic Networks for an Industrial Network, March 2017 – (Isabelle Chrisment as reviewer).
- Yoann Bertrand, PhD in Computer Sciencce from Université Côte d'Azur, France. Title: Access control policies and companies data transmission management, March 2017 – (as examiner).
- Eric Asselin, Phd in Computer Science from Université de Toulouse, France. Title: Système de détection d'intrusion adapté au système de communication aéronautique ACARS, June 2017 – (Isabelle Chrisment as reviewer)

- Xiao Han, Phd in Computer Science from TELECOM ParisTech, France. Title: Measurement and Monitoring of Security from the Perspective of a Service Provider, September 2017 – (Isabelle Chrisment as reviewer)
- Bruno Dorsemaine, Phd in Computer Science from TELECOM ParisTech, France. Title: Conception et expérimentation d'un modèle de sécurité dédié à un système d'information interagissant avec des infrastructures d'objets connectés, October 2017 – (Isabelle Chrisment as examiner)
- Rishikesh SAHAY, Phd in Computer Science from TELECOM ParisTech, France. Title: Policy-Driven Autonomic Cyberdefense using Software Defined Networking, November 2017 – (Isabelle Chrisment as examiner)
- Florian Grandhomme, Phd in Computer Science from Université de Rennes 1, France. Title: Études de protocoles de routage dynamique externe de type BGP dans un environnement réseaux tactiques ad hoc mobiles : faisabilité et performance, November 2017 – (Isabelle Chrisment as examiner)
- Celestin Matte, Phd in Computer Science from Université de Lyon, Insa, France. Title: Wi-Fi Tracking: Fingerprinting Attacks and Counter-Measures, December 2017 – (Isabelle Chrisment as examiner)
- Zied Aouini, Phd in Computer Science from Université de la Rochelle, France. Title: Traffic Monitoring in Home Networks: From Theory to Practice, December 2017 – (Isabelle Chrisment as reviewer)
- Deepak Subramanian, Phd in Computer Science from CentraleSupélec, France. Title: Information Flow Control for the Web Browser through a Mechanism of Split Qddress, December 2017 – (Isabelle Chrisment as reviewer)
- Emilie Bérard-Deroche, Phd in Computer Science from Université de Toulouse - INP Toulouse, France. Title: Distribution d'une architecture modulaire intégrée dans un contexte hélicoptère, December 2017 – (Yeqiong Song as reviewer)
- Alemayehu Addisu Desta, Phd in Computer Science from Université de Paris-Est, France. Title: Energy Supply and Demand Side Management in Industrial Microgrid Context, December 2017 – (Yeqiong Song as examinator)
- Muhammad Agus Zainuddin, Phd in Computer Science from Université de Franche-Comté, France. Title: Efficient Low Layer Techniques for Electromagnetic Nanocommunication Networks, March 2017 – (Yeqiong Song as reviewer)

Team members participated to the following mid-term Ph.D. defense committees in:

- Philippe Pittoli, PhD Student in Université de Strasbourg, France. Title : Architecture de sécurité pour l'Internet des Objets, July 2017 – (Isabelle Chrisment as external reviewer)
- Antoine Vastel, PhD Student in Université de Lille, France. Title; Browser Fingerprinting: Privacy, Security and tracking, September 2017 – (Isabelle Chrisment as external reviewer)
- John Harrison Kurunathan, PhD Student in the University of Porto, Portugal. Title: Improving QoS for IEEE 802.15.4e Networks, September 2017 – (Yeqiong Song as external reviewer)

Team members participated to the following Habilitation Degree defense committees:

- Mathieu Bouet, Habilitation Degree in Computer Science from Université Pierre et Marie Curie - Sorbonne Universités, France. Title: Software networks : Orchestration, resilience, and programmability concerns, July 2017 – (Olivier Festor as reviewer).
- Nader Mbarek, Habilitation Degree in Computer Science from Université de Bourgogne, France. Title: Contributions à la Gestion Autonome et la Garantie du Niveau de Service dans les Environnements Cloud, Radio Maillés et Mobiles, July 2017 – (Olivier Festor as reviewer).
- Osman Salem, Habilitation Degree in Computer Science from Université Paris Descartes, France. Title: Anomaly Detection in Wireless Body Area Networks for Reliable Healthcare Monitoring, April 2017 – (Olivier Festor as reviewer).

- Francis Colas, Habilitation Degree in Computer Science from Université de Lorraine, France. Title: Modélisation bayésienne et robotique, May 2017 – (Yeqiong Song as examinator).
- Hanen Idoudi, Habilitation Degree in Computer Science from Université Jean Jaures, Toulouse 2, France. Title: Contributions à l'amélioration des communications dans les réseaux sans fil multi-sauts, December 2017 – (Yeqiong Song as reviewer).
- Karine Deschinkel, Habilitation Degree in Computer Science from Université de Franche-Comté, France. Title: Nouveaux modèles de programmation linéaires et de flots pour la résolution de problèmes d'optimisation difficiles, June 2017 – (Yeqiong Song as president).

10.3. Popularization

- Isabelle Chrisment was in charge of the scientific part of the 4th module (connecter le réseau) in the Class'Code project https://project.inria.fr/classcode/classcode-in-english/, aiming at helping teachers and educators for introducing computer science to childrens aged from 8 to 14 years;

11. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] W. M. SHBAIR.*Service-Level Monitoring of HTTPS Traffic*, Université de Lorraine, May 2017, https://tel.archives-ouvertes.fr/tel-01649735.

[2] J. VAUBOURG.*Integration of IP network models to DEVS multi-models, for cyber-physical system co-simulations*, Université de Lorraine, April 2017, https://tel.archives-ouvertes.fr/tel-01647881.

Articles in International Peer-Reviewed Journal

[3] F. DE TURCK, J.-M. KANG, H. CHOO, M.-S. KIM, B.-Y. CHOI, R. BADONNEL, J. W.-K. HONG.*Softwarization of networks, clouds, and internet of things*, in "International Journal of Network Management", March 2017, vol. 27, n° 2, p. 1-2 [*DOI :* 10.1002/NEM.1967], https://hal.inria.fr/hal-01630838.

[4] A. MAYZAUD, R. BADONNEL, I. CHRISMENT.*A Distributed Monitoring Strategy for Detecting Version Number Attacks in RPL-Based Networks*, in "IEEE Transactions on Network and Service Management", June 2017, vol. 14, n° 2, p. 472 - 486 [*DOI :* 10.1109/TNSM.2017.2705290], https://hal.inria.fr/hal-01630840.

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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:

A5.3. - Image processing and analysis
A5.4. - Computer vision
A5.4.1. - Object recognition
A5.4.5. - Object tracking and motion analysis
A5.4.6. - Object localization
A5.6. - Virtual reality, augmented reality
A5.10.2. - Perception

Other Research Topics and Application Domains:

B2.6. - Biological and medical imaging
B5.9. - Industrial maintenance
B9.4.3. - Physics

1. Personnel

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Erwan Kerrien [Inria, Researcher]

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Gilles Simon [Univ de Lorraine, Associate Professor]
Frédéric Sur [Univ de Lorraine, Associate Professor, HDR]
Pierre-Fredéric Villard [Univ de Lorraine, Associate Professor]
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Vincent Gaudilliere [Inria, DGA Rapid]
Daryna Panicheva [Univ de Lorraine, from Oct 2017]
Raffaella Trivisonne [Inria, co-supervision with EPC MIMESIS]
Charlotte Delmas [Defended on Nov, 10th]
Pierre Rolin [until Mar 2017]

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Cong Yang [Univ de Lorraine, until Sep 2017]

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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 advances 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,...)

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 robust 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 [9]. 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 performed 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 of obtaining realistic and possibly dynamic models of organs suitable for real-time simulation [14].

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 [7] (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 imaging 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 the training of surgeons or the re-education of patients.

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 [8]. In the medical field, specific methods based on an adaptive evolutionary optimization strategy have been designed for estimating respiratory parameters [10]. 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 the University Hospital of Nancy and GE Healthcare in interventional neuroradiology. Our common aim is to develop a multimodal 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 Auvergne 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. Highlights of the Year

5.1. Highlights of the Year

Our paper entitled "The grid method for in-plane displacement and strain measurement: a review and analysis" [23] has been awarded with the Fylde Best Paper in Strain Prize 2016 by the British Society for Strain Measurement (BSSM).

6. New Software and Platforms

6.1. Ltrack

KEYWORDS: Augmented reality - Visual tracking
FUNCTIONAL DESCRIPTION: The Inria development action 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.
NEWS OF THE YEAR: A recovery procedure based on key-frames has been designed when the number of inliers tracked keypoints is too small.

- Contact: Marie-Odile Berger

6.2. PoLAR

Portable Library for Augmented Reality

FUNCTIONAL DESCRIPTION: PoLAR (Portable Library for Augmented Reality) is a framework which aims to help creating graphical applications for augmented reality, image visualization and medical imaging. PoLAR was designed to offer powerful visualization functionalities without the need to be a specialist in Computer Graphics. The framework provides an API to state-of-the-art libraries: Qt to build GUIs and OpenSceneGraph for high-end visualization, for researchers and engineers with a background in Computer Vision to be able to create beautiful AR applications, with little programming effort. The framework is written in C++ and published under the GNU GPL license

- Contact: Erwan Kerrien
- URL: http://polar.inria.fr

6.3. Fast>VP

KEYWORDS: Vanishing points - Image rectification
FUNCTIONAL DESCRIPTION: Fast>VP is a fast and effective tool to detect vanishing points in uncalibrated images of urban or indoor scenes.

This tool also allows automatic rectification of the vertical planes in the scene, namely generating images where these planes appear as if they were observed from a fronto-parallel view.

It is the Matlab implementation of the algorithm described in [6].

- Contact: Gilles Simon
- URL: https://members.loria.fr/GSimon/fastvp/

6.4. TheGridMethod

The grid method toolbox
KEYWORD: Experimental mechanics
FUNCTIONAL DESCRIPTION: 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 mechanical testing.

- Contact: Frédéric Sur
- URL: http://www.thegridmethod.net/

7. New Results

7.1. Matching and localization

Participants: Marie-Odile Berger, Vincent Gaudilliere, 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 his PhD thesis [12], P. Rolin has 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 additional computational cost.

Vanishing point detection

Accurate detection of *vanishing points* (VPs) is a prerequisite for many computer vision problems such as camera self-calibration, single-view structure recovery, video compass, robot navigation and augmented reality, among many others. we are interested in VP detection from uncalibrated monocular images. As any two parallel lines intersect in a VP, grouping line segments is a difficult problem that often yields a large number of spurious VPs. However, many tasks in computer vision, including the examples mentioned above, only require that the vertical (so-called *zenith*) VP and two or more horizontal VPs are detected. In that case, a lot of spurious VPs can be avoided by first detecting the zenith and the *horizon line* (HL), and then constraining the horizontal VPs on the HL. The zenith is generally easy to detect, as many lines converge towards that point in man-made environments. However, until recently, the HL was detected as an alignment of VPs, which led to a “chicken-and-egg” problem.

Last year, we showed that, assuming that the HL is inside the image boundaries, this line can usually be detected as an alignment of oriented line segments. This comes from the fact that any horizontal line segment at the height of the camera’s optical center projects to the HL regardless of its 3-D direction. In practice, doors, windows, floor separation lines but also man-made objects such as cars, road signs, street furniture, and so on, are often placed at eye level, so that alignments of oriented line segments around the HLs are indeed observed in most images from urban or indoor scenes. This allowed us to propose a new method for VP detection, that was fast in execution and easy to implement. However, it was only middle rank in terms of accuracy. This year, we effectively put the HL detection into an *a contrario* framework. This transposal along with other improvements allows us to obtain top-ranked results in terms of both rapidity of computation and accuracy of the HL, along with more relevant VPs than with the previous top-ranked methods. This work has been submitted to CVPR 2018 (IEEE Conference on Computer Vision and Pattern Recognition).

Facade detection and localization

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 proposed in [19] a novel object proposals method specific to building facades. We define new image cues that measure typical facade characteristics such as semantics, symmetry and repetitions. They are combined to generate a few facade candidates in urban environments fast. We show that our method outperforms state-of-the-art object proposals techniques for this task on the 1000 images of the Zurich Building Database. We demonstrated the interest of this procedure for augmented reality through facade recognition and camera pose initialization. In a very time-efficient pipeline we classify the candidates and match them to a facade references database using CNN-based descriptors. We proved that this approach is more robust to severe changes of viewpoint and occlusions than standard object recognition methods.

We are currently investigating ways to perform registration from this set of facade proposals. As point-based approaches may be inefficient to perform image/model matching due to changes in the illumination conditions, we propose to rely on semantic segmentation to improve the accuracy of this initial registration. Registration is here improved through an Expectation-Maximization framework. We especially introduce a Bayesian model that uses prior semantic segmentation as well as geometric structure of the facade reference modeled by L p Gaussian mixtures. This work has been submitted to CVPR’2018.

AR in industrial environments

As industrial environments are normally inundated with textureless objects and specular surfaces, it is difficult to capture enough features and build accurate 3D models for camera pose estimation using traditional 2D/3D matching-based approaches. Moreover, as people usually check industrial objects with free motions, recent CNN-based approaches could easily fail if the training data is not properly collected (e.g. does not cover enough views around the objects) and augmented (e.g. over-zoomed and over-augmented). For these challenges, we presented a novel protocol for six degrees of freedom (6-DOF) camera pose learning and estimation without any 3D reconstruction and matching processes. In particular, we proposed a visually controllable method to collect sufficient training images and their 6-DOF camera poses from different views and camera-object distances. Building upon this, we proposed a transfer learning scheme to train convolutional neural networks to detect objects and estimate the coarse camera pose from a single RGB image in an end-to-end manner. Experiments show that the trained convolutional network estimates each camera pose in about 5 ms and obtains approximately 13.3mm and 4.8 $\deg$ accuracy, which is compatible for training or maintenance tasks in industrial environments.

This work has been submitted to WACV 2018 (IEEE Winter Conf. on Applications of Computer Vision), and an extended version to TVCG (IEEE Transactions on Visualization and Computer Graphics).

7.2. Handling non-rigid deformations

Participants: Marie-Odile Berger, Jaime Garcia Guevara, Daryna Panicheva, Pierre-Frédéric Villard.

Elastic multi-modal registration

Image-guided hepatic surgery is progressively becoming a standard for certain interventions. However, requirements on limited radiation dosis result in lower quality images, making it difficult to localize tumors and other structures of interest. Within J. Guevara's PhD thesis, we have proposed an automatic registration method exploiting the matching of the vascular trees, visible in both pre- and intra-operative images. The graphs are automatically matched using an algorithm combining Gaussian Process Regression and biomechanical model [20]. Indeed, Gaussian Process regression allows for a rigorous and fast error propagation but is extremely versatile. On the contrary, using biomecanical transformations is slower but provides physically correct hypotheses. Integrating the two approaches allows us to dramatically improve the quality of the matching for moderate or large organ deformations while reducing significantly the computational cost.

Individual-specific heart valve modeling

In this work, we focused on the segmentation of the valve cords. As dataset, we used 8 CT images of porcine hearts. Those data were acquired during various times with a microCT scan machine.

Within D. Panicheva's Master thesis, we worked on modeling the mitral valve chordae by applying a RANSAC-based method designed to extract cylinders with elliptical basis from a set of 3D contour points. To limit the search area, the results of segmentation obtained with classical methods for tubular structures extraction were used as initial assumptions of cords location.

The proposed method allows us to significantly improve cords segmentation results compared with classical methods, in particular, the section size and the endpoints of the cords are accurately defined which is important for future mechanical modeling of the mitral valve.

INVIVE: The Individual Virtual Ventilator: Image-based biomechanical simulation of the diaphragm during mechanical ventilation

The motivation for the project is the serious medical condition, called ventilator induced diaphragmatic dysfunction (VIDD). During mechanical ventilation, air is pushed into the lungs resulting in a passive displacement of the diaphragm. This unnatural forcing results in loss of function in the muscle tissue. Our goal is to develop a simulator that allows for an in-silico exploration of the respiratory function with and without mechanical ventilation in combination with intervention measures that can reduce or prevent the risk for VIDD in the patients.

In the first year of the project, we worked on extracting a mesh from the segmented medical data that includes the boundary conditions. This work relies on analyzing the physiological constrains (rib motions, thoracic, abdominal and lung pressures) that can be measured.

We also worked on a method to solve differential equations on a complex geometric domain using the Radial Basis Function Partition of Unity Collocation Method (RBF-PUM). To use RBF-PUM for solving differential equations a covering of the domain has to be formed. The test implemented Poisson's diffusion equation on a domain defined by the diaphragm geometry. The diaphragm is not an easy case due to its thickness and shape.

This work is funded by the Swedish Research Council and realized within a collaboration with Uppsala University.

7.3. 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. Moreover only two projective fluoroscopic views are available at most, with absolutely no depth hint. As a consequence, 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, our project aims 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. She presented her research and results about fluoroscopic image segmentation, live stereo reconstruction of the guidewire, and fast 3D coil reconstruction, together with in-depth validation, in her PhD manuscript [11].

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. We investigated various image and mechanical constraints, and proposed an efficient constrained shape from template approach where a set of radio-opaque markers on the catheter are tracked in the fluoroscopic images, and the surface of the vessel defines a set of unilateral constraints to prevent the catheter from crossing the vessel wall [22]. In particular, a constraint on the insertion point of the catheter at the groin was necessary to retrieve an accurate 3D shape of the micro-device.

7.4. Assessing metrological performance in experimental mechanics

Participant: Frédéric Sur.

In experimental mechanics, displacement and strain fields are estimated through the analysis of the deformation of patterns deposited on the surface of the tested specimen. Regular patterns such as grids are processed with spectral methods (the so-called "grid method"), and random speckle patterns are processed with digital image correlation (DIC). The scientific contribution obtained in 2017 concerns the comparison of the grid method and DIC. Since neither guidelines nor precise standard are available to perform a fair comparison between them, a methodology must first be defined. In [13], it is proposed to rely on three metrological parameters, namely the displacement resolution, the bias and the spatial resolution, which are not independent but linked.For the value of the bias fixed in the study of [13], the grid method features a better compromise than subset-based local DIC between displacement resolution and spatial resolution, in spite of its additional cost due to grid depositing. Work in progress concerns several aspects of DIC-based methods. In particular, we worked on synthetic speckle image rendering: ground truth databases are indeed crucial to assess the performance of the algorithms estimating displacement fields. It is, however, not straightforward to control any aspect of the rendering algorithm to ensure that performance assessment is not biased by the rendering algorithm. In addition, a popularization paper has been published in ERCIM News [15]. This work is part of a collaboration between Magrit project-team and Institut Pascal (Clermont-Ferrand).

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts 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. The PhD thesis of Charlotte Delmas started in April 2013 and ended in November 2017 and was supervised by M.-O. Berger and E. Kerrien. In her work, C. Delmas developped methods to reconstruct the micro-tools in 3D from fluoroscopy imaging. This will help clinical gesture by providing the physician with a better understanding of the relative positions of the tools and of the pathology.

9. Partnerships and Cooperations

9.1. Regional Initiatives

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 Guevara started in October 2015 and is funded by the Région Lorraine. It is co-supervised by M.-O. Berger and S. Cotin (MILESIS, Strasbourg). It follows on from our past works and aims at improving the reliability and the robustness of AR-based clinical procedures.

A one year post-doc position was granted by the Region Lorraine and the Université de Lorraine. Cong Yang started this position in November 2016 and ended in October 2017. He developed algorithms for object recognition in large-scale industrial environments (factories, vessels, ...), with the aim to enrich the operator's field of view with digital information and media. The main issues concerned the size of the environment, the nature of the objects (often non textured, highly specular, ...) and the presence of repeated patterns.

9.2. National Initiatives

9.2.1. Projet RAPID EVORA

Participants: M.-O. Berger, V. Gaudillière, G. Simon, C. Yang.
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 in December 2016.

9.2.2. Project funded by GDR ISIS in collaboration with Institut Pascal

Participant: F. Sur.
Between September 2014 and September 2017, we have been engaged in a collaboration with Institut Pascal funded by GDR ISIS. The aim of this project was the investigation of image processing tools for enhancing the metrological performance of contactless measurement systems in experimental mechanics.

9.2.3. AEN Inria SOFA-InterMedS

Participants: R. Anxionnat (CHU Nancy), 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. Two PhD students - R. Trivisonne and J. Guarcia Guevara- are currently co-supervised by the Magrit and the MIMESIS teams.

9.3. International Initiatives

9.3.1. Inria Associate Teams Not Involved in an Inria International Lab

9.3.1.1. CURATIVE

Title: CompUteR-based simulAtion Tool for mItral Valve rEpair

International Partner (Institution - Laboratory - Researcher):

Harvard University (United States) - Harvard Biorobotics Lab (HBL) - Robert Howe

Start year: 2017

See also: https://team.inria.fr/curative/

The mitral valve of the heart ensures one-way flow of oxygenated blood from the left atrium to the left ventricle. However, many pathologies damage the valve anatomy producing undesired backflow, or regurgitation, decreasing cardiac efficiency and potentially leading to heart failure if left untreated. Such cases could be treated by surgical repair of the valve. However, it is technically difficult and outcomes are highly dependent upon the experience of the surgeon.

One way to facilitate the repair is to simulate the mechanical behavior of the pathological valve with subject-specific data. Our main goal is to provide surgeons with a tool to study solutions of mitral valve repairs. This tool would be a computer-based model that can simulate a potential surgical repair procedure in order to evaluate its success. The surgeons would be able to customize the simulation to a patient and to a technique of valve repair. Our methodology will be to realistically simulate valve closure based on segmentation methods faithful enough to capture subject-specific anatomy and based on a biomechanical model that can accurately model the range of properties exhibited by pathological valves.

During the first year, we worked on three aspects of this project: i) developing a fast image-based mitral valve simulation, ii) extracting the mitral valve chordae from a CT scan (see section New Results) and iii) developing a Cosserat model for catheter robot for heart surgical procedures. The work on fast image-based mitral valve simulation has been accepted to the The International Journal of Medical Robotics and Computer Assisted Surgery [17].

9.4. International Research Visitors

9.4.1. Visits of International Scientists

Douglas Perrin, a senior researcher at Harvard University (http://people.seas.harvard.edu/~dperrin), visited the MAGRIT team from 05/29/17 to 06/02/17. He gave a talk to the Department 1 in Loria, he helped out with scientific understanding of the mitral valve anatomy and he provided advice to Daryna Panicheva supervision during one week.

Thomas Waite, an undergrad student at Harvard University, visited the MAGRIT team from 06/05/17 to 06/09/17. He gave a talk to the Department 1 in Loria, he worked with Pierre-Frédéric Villard on modeling a heart surgical catheter robot with Cosserat model and started writing a journal paper on this subject.

9.4.2. Visits to International Teams

9.4.2.1. Research Stays Abroad

Pierre-Frederic Villard spent one month (August 2017) at Uppsala University working on the INVIVE project http://www.it.uu.se/research/scientific_computing/project/rbf/biomech. His work there includes supervising PhD student Igor Tominec, meeting with a physiologist expert in respiration muscles and working on both the mesh and the boundary conditions in the case of a passive diaphragm.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. Member of the Organizing Committees

- M.-O Berger co-organized with E. Marchand (IRISA) a one-day workshop on Augmented Reality in Paris in June 2017.

10.1.2. Scientific Events Selection

10.1.2.1. Member of the Conference Program Committees

- M.-O. Berger was a member of the program committee of: International Conference on Robotic and automation (ICRA 2016), International Conference on Information Processing in Computer assisted interventions (IPCAI 2017), International Conference on Robotics and Automation (IROS 2017), International Symposium on Mixed and Augmented Reality (ISMAR 2017)
- E. Kerrien was a member of the program committee of the Medical Image Computing and Computer Assisted Interventions Conference (MICCAI 2017).
- G. Simon was a member of the program committee of IEEE Virtual Reality 2018
- P.-F Villard was a member of the program committee of IADIS Computer Graphics, Visualization, Computer Vision and Image Processing 2017, and of the Eurographics Workshop on Visual Computing for Biology and Medicine 2017.

10.1.3. Journal

10.1.3.1. Reviewer - Reviewing Activities

The members of the team reviewed articles in IEEE Transactions on Pattern Analysis and Machine Intelligence, IEEE Transactions on Multimedia, Experimental Mechanics, Traitement du Signal, IEEE Transactions on Biomedical Engineering.

10.1.4. Invited Talks

- Marie-Odile Berger was a keynote speaker at ISMAR'2017.
- Pierre-Frederic gave a seminar at the department of information technology of Uppsala University on August 30th. Title: 'Application in treatment planning, training simulators and on-line treatment' http://user.it.uu.se/~maya/seminar_abstracts/sem_fall17/PFVillard.
- Pierre-Frederic Villard gave a talk at the Harvard Biorobotics Lab on October 31st. Title: 'Automatic Reconstruction of Mitral Valve Chordae'.

10.1.5. Scientific Expertise

- Marie-Odile Berger is the president of the Association française pour la reconnaissance et l'interprétation des formes (AFRIF)

10.1.6. 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 on the topic of manufacturing (KIC Added-value Manufacturing).
- E. Kerrien and G. Simon were members of selection committees for Assistant Professor hiring.

10.2. Teaching - Supervision - Juries

10.2.1. 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 punctual 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 (P.-F. Villard).
- Licence: Image processing, 30h, IUT Saint-Dié des Vosges (P.-F. Villard).
- Licence: 3D programming, 30h, IUT Saint-Dié des Vosges (P.-F. Villard).
- Game design with Unity3D , 15h, IUT Saint-Dié des Vosges (P.-F. Villard).
- Introduction to augmented reality, 6h, IUT Saint-Dié des Vosges (P.-F. Villard).
- Master: Signal analysis, 50 h, Université de Lorraine (F. Sur).
- Master: Augmented reality, 24 h, Télécom-Nancy, Université de Lorraine (G. Simon).
- Master : Introduction to computer vision, 12h, Université de Lorraine ((M.-O. Berger).
- Master : Shape recognition, 15 h, Université de Lorraine (M.-O. Berger).
- Master : Computer vision: foundations and applications, 15 h, Université de Lorraine (M.-O. Berger).
- Master : Introduction to image processing, 21 h, École des Mines de Nancy (M.-O. Berger, R. Kerrien)
- Master : Image processing for Geosciences, ENSG, 12h (M.-O. Berger).
- Master : Introduction to signal processing and applications, 21 h, Ecole des Mines de Nancy (F. Sur).
- Master : Augmented reality, 24h, M2 IHM Metz (G. Simon).
- Master : Augmented reality, 3 h, SUPELEC Metz (G.simon).
- Master : Virtual worlds, 10h, M2 Cognitive Sciences and Applications, UFR Math-Info, Université de Lorraine (P.-F. Villard).

Frédéric Sur is the head of the Industrial Engineering and Applied Mathematics department at Mines Nancy.

10.2.2. Supervision

PhD: Pierre Rolin, Calcul de pose par simulation de points de vue pour la réalité augmentée, octobre 2013, Marie-Odile Berger, Frédéric Sur. PhD defended in March 2017.

PhD: Charlotte Delmas, Reconstruction 3D des outils chirurgicaux en radiologie interventionnelle, avril 2013, Marie-Odile Berger, Erwan Kerrien. PhD defended in november 2017.

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.

PhD in progress: Daryna Panicheva, Image-based Biomechanical Simulation of Mitral Valve Closure, octobre 2017, Marie-Odile Berger, Pierre-Frédéric Villard.

10.2.3. Juries

Marie-Odile Berger was external reviewer of the PhD of Canseng Jiang (Université de Bourgogne), Angélique Loesch (Université de Clarmont Auvergne) and Shaifali Parashar (Université de Clermont Auvergne).

10.3. Popularization

Members of the team participate on a regular basis, to scientific awareness and mediation actions.

- 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 “Maison pour la Science de Lorraine, 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 2017” at the Faculté de Sciences et Technologies of the Université de Lorraine. He presented unplugged activities of 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.

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[12] P. ROLIN.*Viewpoint synthesis for camera pose initialisation*, Université de Lorraine, March 2017, https://hal.archives-ouvertes.fr/tel-01536649.

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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 Medicine

Table of contents

Team MIMESIS

Creation of the Team: 2015 July 01

Keywords:

Computer Science and Digital Science:

A2.5. - Software engineering
A3.1.1. - Modeling, representation
A3.1.4. - Uncertain data
A3.2.2. - Knowledge extraction, cleaning
A5.1. - Human-Computer Interaction
A5.3.4. - Registration
A5.4.4. - 3D and spatio-temporal reconstruction
A5.4.5. - Object tracking and motion analysis
A5.6. - Virtual reality, augmented reality
A6.1.1. - Continuous Modeling (PDE, ODE)
A6.1.5. - Multiphysics modeling
A6.2.8. - Computational geometry and meshes

Other Research Topics and Application Domains:

B2.4. - Therapies
B2.4.3. - Surgery
B2.6. - Biological and medical imaging
B2.7. - Medical devices
B2.7.1. - Surgical devices

1. Personnel

Research Scientists

Stéphane Cotin [Team leader, Senior Researcher, HDR]
David Cazier [Univ de Strasbourg, Senior Researcher, HDR]
Igor Peterlik [Inria, Researcher]
Hadrien Courtecuisse [CNRS, Researcher]
Lionel Untereiner [Univ de Strasbourg, Researcher, from Oct 2017]

Technical Staff

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Bruno Marques [Inria]
Frederick Roy [Inria]
Etienne Schmitt [Inria, until Feb 2017]

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Raffaella Trivisonne [Inria]
Yinoussa Adagolodjo [Univ de Strasbourg]
Jaime Garcia Guevara [Inria]
Andréa Mendizabal [Univ de Strasbourg, from Sep 2017]
Sergei Nikolaev [Inria, from May 2017]

Jean-Nicolas Brunet [Inria, from Jun 2017]

Post-Doctoral Fellows

Christoph Paulus [Inria, from Apr 2017]
Nazim Haouchine [Inria, until Jan 2017]
Antoine Petit [Inria, from Jun 2017]

Administrative Assistants

Isabelle Blanchard [Inria]
Ouiza Herbi [Inria]

2. Overall Objectives

2.1. Team Overview

At the end of 2011, a part of Inria team SHACRA moved from Lille to Strasbourg to join the newly created Institute of Image-guided Surgery (IHU) 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: to create a synergy between clinicians and scientists to develop new technologies that can redefine healthcare with a strong emphasis on clinical translation.

The global objective of research team MIMESIS is to create a *synergy between clinicians and scientists* to develop new technologies that can redefine healthcare, with a strong emphasis on clinical translation. To achieve this goal, we have joined IHU and we collaborate with numerous partners in both academic and private domain.

The scientific objectives of the 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. We now propose to focus our research on the use of real-time simulation for per-operative guidance. The underlying objectives include numerical techniques for real-time computation and data-driven simulation dedicated to patient-specific modeling. 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. Our research projects are currently organized around three main axes:

- **Real-time Patient-Specific Computational Models**
- **Adaptive Meshing and Advanced Simulation Techniques**
- **Image-driven Simulation**

The SOFA framework is used to integrate our various contributions as a means to facilitate validation and technology transfer.

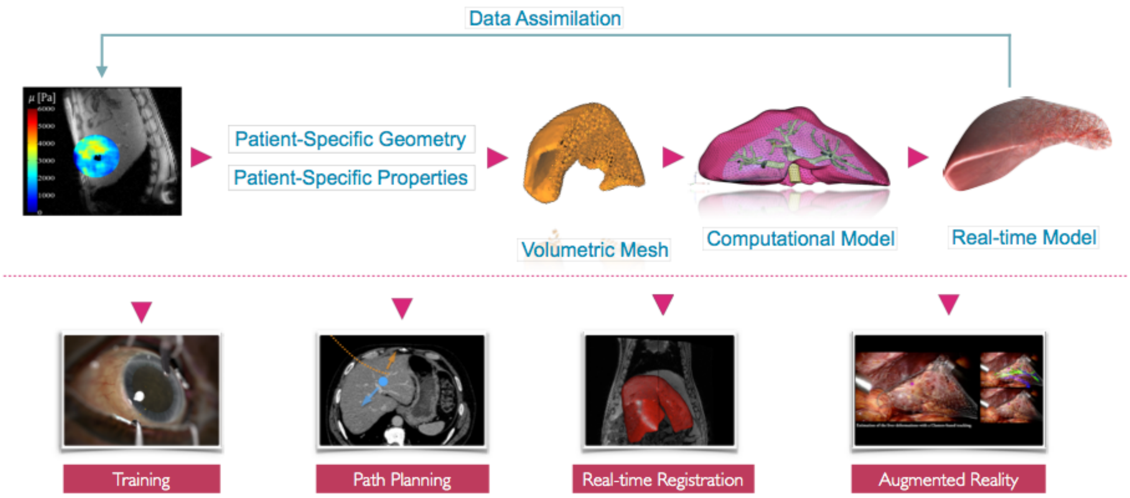

Figure 1. Patient-specific simulations: from training to intra-operative guidance.

3. Research Program

3.1. Real Time Patient-Specific Computational Models

Accounting for the biomechanics and physiology of organs under various stimuli requires employment of *biomechanical models*. These must describe biophysical phenomena such as soft-tissue deformation, fluid dynamics, electrical propagation, or heat transfer. We aim at simulating the impact of certain therapies (such as cryosurgery or radio-frequency ablation) and representing the behavior of complex organs such as the brain, the liver or the heart.

An important part of our research is dedicated to the development of new accurate models that remain compatible with real-time computation [6]. Such advanced models do not only permit to increase the realism of future training systems, but they act as a bridge toward the development of patient-specific preoperative planning as well as augmented reality tools for the operating room [5] [40], [54]. Yet, patient-specific planning or per-operative guidance also requires the models to be parametrized with patient-specific biomechanical data. Our objective is the study of hyper-elastic models and their validation for a range of tissues. Preliminary work has been done through two collaborations, one with the biomechanical lab in Lille (LML) [42], and the biomechanics group from the Icube laboratory in Strasbourg on the development and validation of liver and kidney models [52].

Another important research topic is related to model reduction through various approaches, such as Proper Generalized Decomposition (PGD) [35]. Similar approaches, such as the use of Krylov spaces, have already been studied in our group recently [33].

We continue our work on cardiac electro-physiology simulation [53], with a focus on patient-specific adaptation of the model. We also study a similar problem, related to the modeling of the electrical conduction in the brain, in the context of Deep Brain Stimulation (DBS) [34], [38]. In this neurosurgical procedure, electrodes are implanted deep into the brain and, connected to a brain pacemaker, send electrical impulses to specific regions. A final objective is to solve optimization problems in the context of heat diffusion. This is a key element of the development of a planning system that can estimate the locations of the electrodes leading to an optimal therapeutic effect [54].

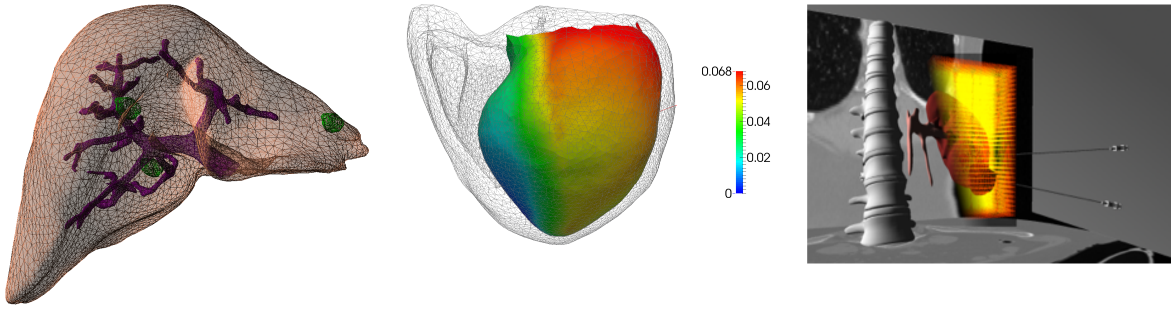

Figure 2. Left: patient-specific liver model with its vascular system. Middle: patient specific depolarization times. Right: cryoablation in the kidney.

3.2. Adaptive Meshing and Advanced Simulation Techniques

Most simulations in the field of biomechanics, physiological modeling, or even computer graphics, are performed using finite element approaches. 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 usually considered as being invariant. However, this is not a realistic assumption if the model is to be employed during a real surgical intervention.

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 [51], [55].

Our second objective is to improve, at the numerical level, the efficiency, robustness, and quality of the simulations. To reach these goals, we essentially rely on two main directions: 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 [35], [36], [46], [47].

We also work on mixed Finite Element Modeling where both tetrahedra and hexahedra can be used at the same time, allowing an ideal compromise between numerical efficiency and mesh adaptation to complex geometries. This research also includes the study of domain decomposition techniques and other coupling techniques for multi-domain multi-physics simulations.

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 [36]. 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 [50], [37]. We will continue exploiting novel methods such as partial factorization [56] and integrate our approach with other techniques such as augmented Lagrangian.

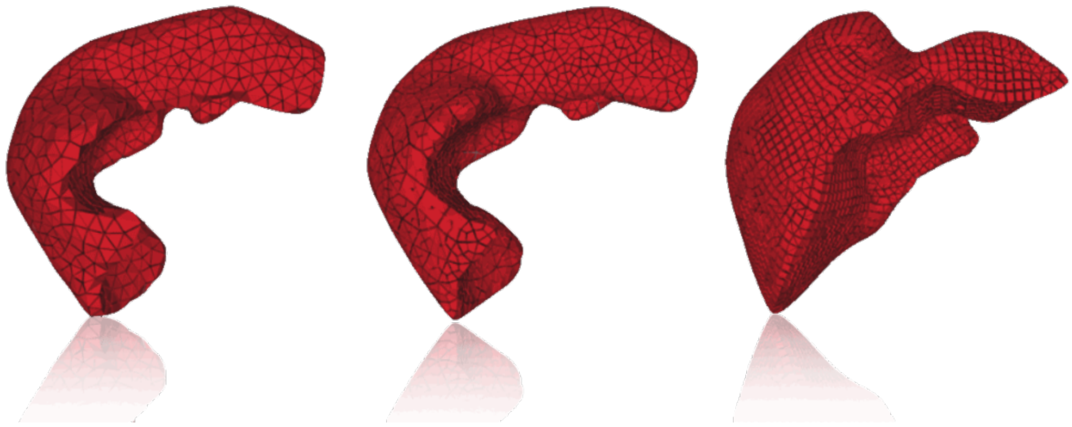

Figure 3. Example of mesh refinement on a complex geometry.

3.3. Data-driven Simulation

Image-driven simulation is a recent area of research that 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.

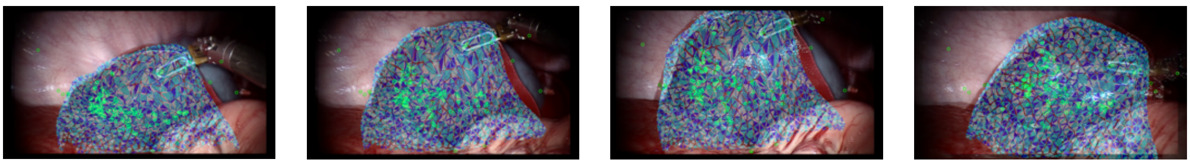

Figure 4. Real-time deformation of a virtual liver according to tissue motion tracked in laparoscopic images.

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 investigating 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 the intra-operative data [45], [43].

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 [40], [48], [39] 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.

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 [41] and its reduced-order versions [44]), 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 [49].

4. Application Domains

4.1. Surgical Training

Virtual training prevents medical students from early manipulation of real patients. The development of simulation used for medical training usually requires important computational power, since realistic behaviours are key to deliver a high-fidelity experience to the trainee. Further, the quality of interaction with the simulator (usually via visual and haptic rendering) is also of a paramount importance. All these constraints make the development of training systems time-consuming thus limiting the deployment of virtual simulators in standard medical curriculum.

4.2. Pre-operative Planning

Beyond training, clinicians ask for innovative tools that can assist them in the pre-operative planning of an intervention. Using the patient information acquired before the operation, physics-based simulations allow to simulate the effect of a therapy with no risk to the patient. The clinicians can thus virtually assess different strategies and select the optimal procedure. Compared to a training simulation, a planning system requires a high accuracy to ensure reliability. Constrained by the time elapsed between the preoperative acquisition and the intervention, the computation must also be efficient.

4.3. Intra-operative Navigation

Besides the surgery training and planning, another major need from clinicians is surgical guidance. While the practician is performing the operation, a guidance system provides enriched visual feedback. This is especially useful with the emergence of minimally invasive surgery (MIS) where the visual information is often strongly limited. It can be used for example to avoid critical area such as vessels or to highlight the position of a tumour during its resection. In the MIS technique, the clinician does not interact with organs directly as in the open surgery, but manipulates instruments inserted through trocars placed in small incisions in the wall of the abdominal cavity. The surgeon can observe these instruments on a display showing a video stream captured by an endoscopic camera inserted through the navel. The main advantage of the method resides in reducing pain and time recovery, in addition to reducing bleeding and risks of infection. However, from a surgical standpoint, the procedure is quite complex since the field of view is considerably reduced and the direct manipulation of organs is not possible.

5. Highlights of the Year

5.1. Highlights of the Year

Prix de thèse 2016 en Génie Biologique et Médical attributed to Rosalie Plantefève for her thesis *Augmented Reality and Numerical Simulation for Resection of Hepatic Tumor*. The award is attributed by three scientific bodies: IEEE EMBS, Société Française de Génie Biologique et Médical, and Alliance pour le Génie Biologique et Médical. In this context, R. Plantefève was invited to submite a paper to the Journal on Innovation and Research in BioMedical Engineering and the manuscript was accepted for publication [17].

Runner up for the best poster award at the IEEE International Symposium on Mixed and Augmented Reality 2017 with the poster *Deformed Reality: Proof of concept and Preliminary Results* [32]. The poster introduced a new paradigm to interactively manipulate objects in a scene in a deformable manner. Using the core principle of augmented reality to estimate a rigid pose over time, the method enables the user to deform the targeted object while it is being rendered with its natural texture, giving the sense of a real-time object editing in the user environment. The results show that the method is capable of opening new ways of not only augmenting the scene but also to interact with it in real by imposing possibly non-linear transformations to selected entities.

The **physics-based image and video editing tool *Calipso* was resumed in *Two-minutes papers* on YouTube.** At the end of 2017, the video has more that 35k views. Calipso is an interactive method for editing images and videos in a physically-coherent manner. The main idea is to perform physics-based manipulations by running a full physics simulation on proxy geometries given by non-rigidly aligned CAD models. Running these simulations allows us to apply new, unseen forces to move or deform selected objects, change physical parameters such as mass or elasticity, or even add entire new objects that interact with the rest of the underlying scene.

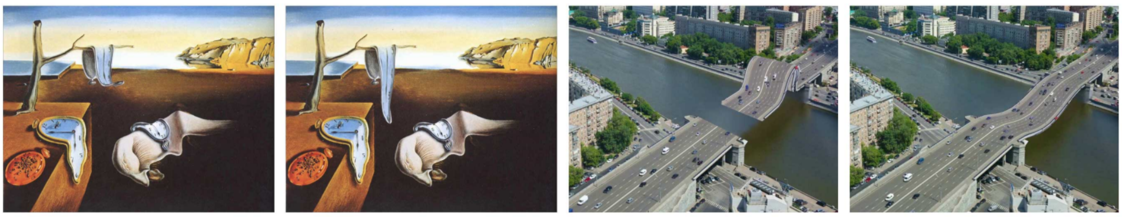

Figure 5. Illustration of Calipso deformed reality on two static images.

6. New Software and Platforms

6.1. SOFA

Simulation Open Framework Architecture
KEYWORDS: Real time - Multi-physics simulation - Medical applications

FUNCTIONAL DESCRIPTION: SOFA is an Open Source framework primarily targeted at real-time simulation, with an emphasis on medical simulation. It is mostly intended for the research community to help develop new algorithms, but can also be used as an efficient prototyping tool. Based on an advanced software architecture, it allows : the creation of complex and evolving simulations by combining new algorithms with algorithms already included in SOFA, the modification of most parameters of the simulation (deformable behavior, surface representation, solver, constraints, collision algorithm, etc.) by simply editing an XML file, the building of complex models from simpler ones using a scene-graph description, the efficient simulation of the dynamics of interacting objects using abstract equation solvers, the reuse and easy comparison of a variety of available methods.

- Participants: Christian Duriez, François Faure, Hervé Delingette and Stéphane Cotin
- Partner: IGG
- Contact: Stéphane Cotin
- URL: http://www.sofa-framework.org

6.2. SofaPardisoSolver

KEYWORDS: Simulation - Linear Systems Solver - Direct solvers - Collision - Numerical simulations
SCIENTIFIC DESCRIPTION: The SofaPardisoSolver allows for fast direct solution of sparse systems of linear equations, using a decomposition (such as LU, LDL and Cholesky) according to the type of the matrix. Moreover, the wrapper allows for employing a partial factorization which brings a significant improvement when solving augmented systems, usually resulting in problems involving collisions and/or domain decomposition.
FUNCTIONAL DESCRIPTION: The SofaPardisoSolver plugin contains a wrapper allowing for an efficient direct solution of a system of linear equations. It also contains an advanced feature which exploits an algorithm of partial decomposition available in Pardiso. This feature significantly accelerates the computation of Schur complement, typically needed to solve linear complementarity problems (LCP). Example of use: collision and contacts.

- Author: Igor Peterlik
- Contact: Igor Peterlik

6.3. SOFA Xray rendering

KEYWORDS: Simulation - Realistic rendering - Real-time rendering - Medical imaging - Medical applications
FUNCTIONAL DESCRIPTION: This work allows to emulate a X-ray scan image within the simulation platform SOFA. By defining the position of an emitter and receptor in the 3D space, an image is rendered. A realistic medical image of organs can thus be obtained from surface meshes (triangulated or quadrangulated) in real-time.

Version compatible with SOFA v17.06

- Authors: Stéphane Cotin and Frédérick Roy
- Contact: Stéphane Cotin

7. New Results

7.1. Augmented Reality in Surgical Navigation

7.1.1. Organ Pose Estimation for Augmented Reality in Hepatic Surgery

Participants: Y. Adagolodjo, R. Trivisonne, H. Courtecuisse, S. Cotin

A contribution focusing on intra-operative organ pose estimation was publihsed at the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2017) [19]. A novel method for semi-automatic registration of 3D deformable models using 2D shape outlines (silhouettes) extracted from a monocular camera view was introduced. The proposed framework is based on the combination of a biomechanical model of the organ with a set of projective constraints influencing the deformation of the model. To enforce convergence towards a global minimum for this ill-posed problem we interactively provide a rough (rigid) estimation of the pose. We show that our approach allows for the estimation of the non-rigid 3D pose while relying only on 2D information. The method is evaluated experimentally on a soft silicone gel model of a liver, as well as on real surgical data, providing augmented reality of the liver and the kidney using a monocular laparoscopic camera. Results show that the final elastic registration can be obtained in just a few seconds, thus remaining compatible with clinical constraints. We also evaluate the sensitivity of our approach according to both the initial alignment of the model and the silhouette length and shape.

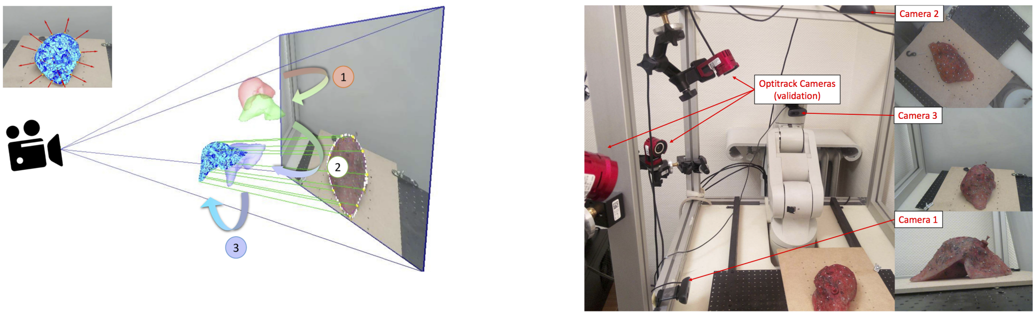

Figure 6. Left: 1) a direct simulation is applied to transform the reconstructed model obtain from the segmentation (red) in a shape close to the 3D position observed in the image (green). 2) A Rigid transformation (blue) is provided by the user to roughly align the model with the contour of the organ segmented in the image (yellow). 3) Projective constraints are applied to the biomechanical model to fit the organ contour and provide the 3D shape w.r.t. the camera position. Right: validation setup.

7.1.2. Image-driven Stochastic Estimation of Boundary Conditions

Participants: N. Haouchine, I. Peterlik, S. Cotin

A novel method was proposed in the context of image-driven stochastic simulation employed in the intra-operative navigation [25]. In the proposed approach, the boundary conditions are modeled as stochastic parameters. The method employs the reduced-order unscented Kalman filter to transform in real-time the probability distributions of the parameters, given observations extracted from intra-operative images. The method is evaluated using synthetic, phantom and real data acquired in vivo on a porcine liver. A quantitative assessment is presented and it is shown that the method significantly increases the predictive power of the biomechanical model employed by a framework implemented the augmented reality for surgical navigation.

7.2. Advanced Numerical Modeling and Simulation

7.2.1. Face-based Smoothed Finite Element Method for Real-time Simulation of Soft Tissue

Participants: A. Mendizabal, C. Paulus, R. Bessard-Duparc, I. Peterlik, S. Cotin

A method based on face-based smoothed finite element method was proposed and applied in the context of modeling of brain shift in [23]. This numerical technique has been introduced recently to overcome the overly stiff behavior of the standard FEM and to improve the solution accuracy and the convergence rate in solid mechanics problems. In this paper, a face-based smoothed finite element method (FS-FEM) using 4-node tetrahedral elements is presented. We show that in some cases, the method allows for reducing the number of degrees of freedom, while preserving the accuracy of the discretization. The method is evaluated on a simulation of a cantilever beam loaded at the free end and on a simulation of a 3D cube under traction and compression forces. Further, it is applied to the simulation of the brain shift and of the kidney's deformation. The results demonstrate that the method outperforms the standard FEM in a bending scenario and that has similar accuracy as the standard FEM in the simulations of brain shift and kidney deformation.

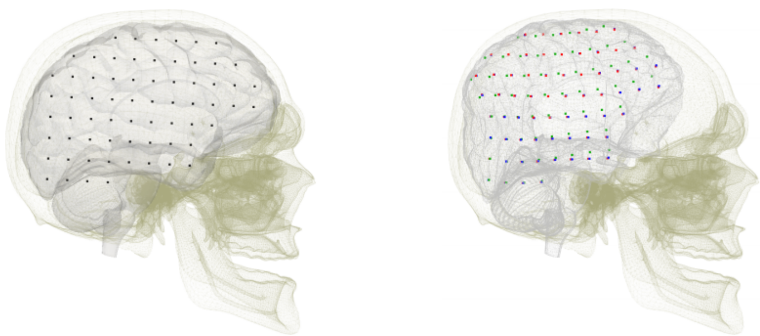

Figure 7. Grid representing tumor positions using a mesh of 7924 elements for linear FEM in blue, FS-FEM in red and non-linear FEM in green after the brain-shift. Left: rest position. Right: position after the deformation due to brain-shift.

7.2.2. Immersed Boundary Method for Real-time

Participants: C. Paulus, S. Cotin

Although the finite element method is widely used as a numerical approach in this area, it is often hindered by the need for an optimal meshing of the domain of interest. The derivation of meshes from imaging modalities such as CT or MRI can be cumbersome and time-consuming. In our contribution [24], we employed the Immersed Boundary Method (IBM) to bridge the gap between these imaging modalities and the fast simulation of soft tissue deformation on complex shapes represented by a surface mesh directly retrieved from binary images. A high resolution surface, that can be obtained from binary images using a marching cubes approach, is embedded into a hexahedral simulation grid. The details of the surface mesh are properly taken into account in the hexahedral mesh by adapting the Mirtich integration method. In addition to not requiring a dedicated meshing approach, our method results in higher accuracy for less degrees of freedom when compared to other element types. Examples on brain deformation demonstrate the potential of our method.

7.2.3. Error Control in Surgical Simulations

Participants: H. Courtecuisse, S. Cotin

A contribution [16] presents the first real-time a posteriori error-driven adaptive finite element approach for real-time simulation and demonstrates the method on a needle insertion problem.

We use corotational elasticity and a frictional needle–tissue interaction model. The problem is solved using finite elements and the refinement strategy relies upon a hexahedron-based finite element method, combined with a posteriori error estimation driven local *h-refinement*, for simulating soft tissue deformation. We

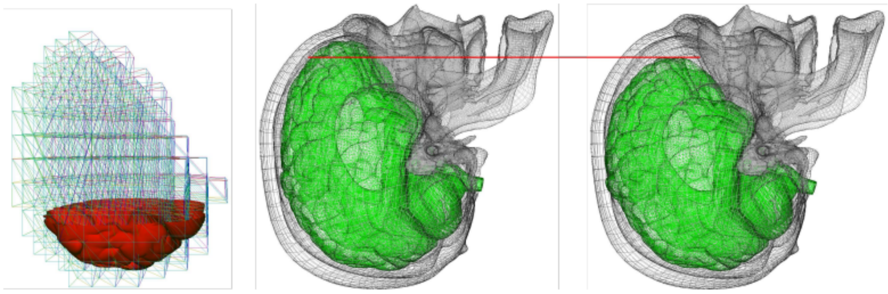

Figure 8. Simulation of brain shift using a detailed surface mesh embedded into an hexahedral grid. Boundary conditions are applied onto the exact surface, not the grid (left).

proposed to control the local and global error level in the mechanical fields (e.g. displacement or stresses) during the simulation. We show the convergence of the algorithm on academic examples, and demonstrate its practical usability on a percutaneous procedure involving needle insertion in a liver. For the latter case, we compare the force displacement curves obtained from the proposed adaptive algorithm with that obtained from a uniform refinement approach. Error control guarantees that a tolerable error level is not exceeded during the simulations. Local mesh refinement accelerates simulations. The work provides a first step to discriminate between discretization error and modeling error by providing a robust quantification of discretization error during simulations.

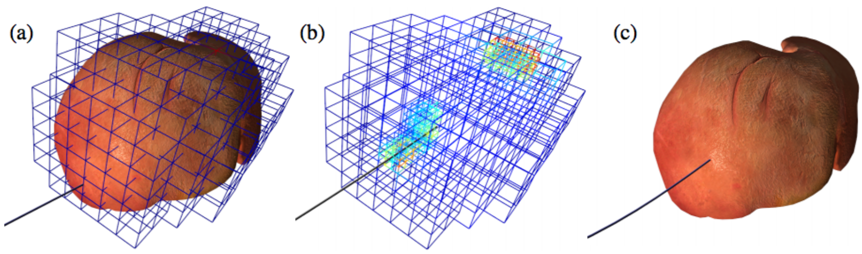

Figure 9. (a) Simulation of needle insertion in a liver; (b) Using dynamic mesh refinement scheme driven by error estimate; (c) Visual depiction. The simulation runs at 22 Hz using a PC with 4 GHz CPU.

7.3. Model-based Image Registration

7.3.1. Intraoperative Biomechanical Registration of the Liver

Participants: R. Plantefève, I. Peterlik, S. Cotin

Different aspects of model-based registration in the context of surgical navigation employing the augmented reality were analyzed in an invited contribution [17] published in the context of the attributed Prix de thèse de former Ph.D. student Rosalie Plantefève. Preoperative images such as computed tomography scans or magnetic resonance imaging contain lots of valuable information that are not easily available for surgeons during an operation. To help the clinicians better target the structures of interest during an intervention, many registration methods that align preoperative images onto the intra-operative view of the organs have been developed. For important organ deformation, biomechanical model-based registration has proven to be a method of choice. Using an existing model-based registration algorithm for laparoscopic liver surgery we investigated the influence of the heterogeneity of the liver on the registration result. It was found that the use of an heterogeneous model does not improve significantly the registration result but increases the computation time necessary to perform the registration.

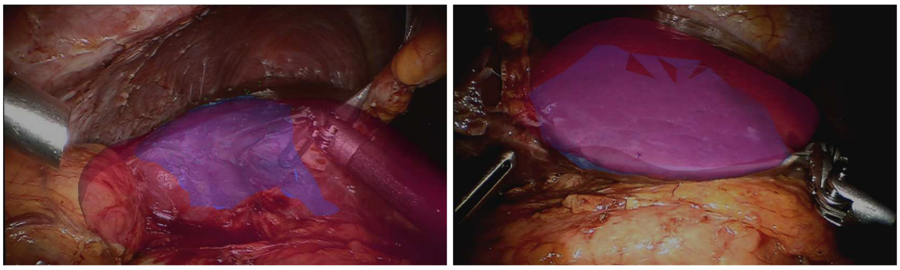

Figure 10. Registration results on in vivo data on two different views of a human liver. The registered mesh is shown in red while the partial reconstructed patch is depicted in blue.

7.3.2. Registration of Cell Nuclei in Cell Microscopy

Participants: I. Peterlik

A contribution *Registration of Cell Nuclei in 2D Live Cell Microscopy* was published in a collaboration with Centre of Biomedical Image Analysis at Masaryk University, Czech Republic [18]. The analysis of the pure motion of sub-nuclear structures without influence of the cell nucleus motion and deformation is essential in live cell imaging. We proposed a 2D contour-based image registration approach for compensation of nucleus motion and deformation in fluorescence microscopy time-lapse sequences. The proposed approach extends our previous approach which uses a static elasticity model to register cell images. Compared to that scheme, the new approach employs a dynamic elasticity model for forward simulation of nucleus motion and deformation based on the motion of its contours. The contour matching process is embedded as a constraint into the system of equations describing the elastic behavior of the nucleus. This results in better performance in terms of the registration accuracy. Our approach was successfully applied to real live cell microscopy image sequences of different types of cells including image data that was specifically designed and acquired for evaluation of cell image registration methods.

7.4. Reconstruction of Geometries from Images

7.4.1. Automatic Skeletonization of Vascular Trees in Pre-operative CT Images

Participants: R. Plantefève, I. Peterlik

An algorithm of an automatic skeletonization of vascularization based on Dijkstra minimum-cost spanning tree was published in [27]. The result is an extension of an existing graph-based method where the vascular topology is constructed by computation of shortest paths in a minimum-cost spanning tree obtained from binary mask of the vascularization. We suppose that the binary mask is extracted from a 3D CT image using automatic segmentation and thus suffers from important artifacts and noise. When compared to the original algorithm, the proposed method (i) employs a new weighting measure which results in smoothing of extracted topology and (ii) introduces a set of tests based on various geometric criteria which are executed in order to detect and remove spurious branches. The method is evaluated on vascular trees extracted from

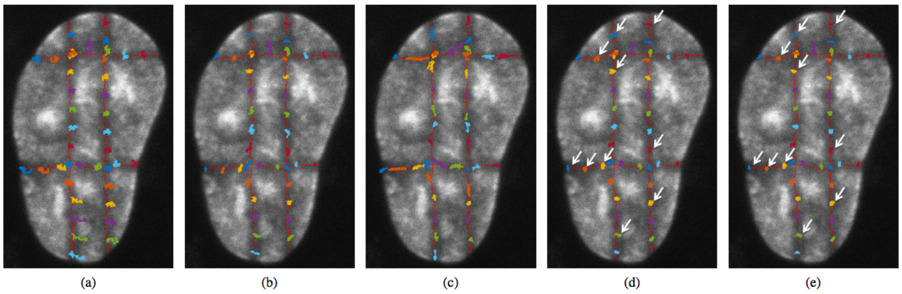

Figure 11. Tracks of line features overlaid with the first image of the sequence. The tracks represent the motion of the points of the line features sampled with 30 pixel interval for better visibility. The tracks are shown for (a) unregistered data, (b) after registration with the contour-based approach [19], (c) after registration with the intensity-based approach [9], (d) after registration with the static version of our approach, and (e) after registration with the proposed dynamic approach. White arrows indicate tracks with the most visible difference between (d) and (e).

abdominal contrast-enhanced CT scans and MR images. The method is quantitatively compared to the original version of the algorithm showing the importance of proposed modifications. Since the branch testing depends on parameters, the para-metric study of the proposed method is presented in order to identify the optimal parametrization.

7.4.2. Template-based Recovery of Elastic Shapes from Monocular Video

Participants: N. Haouchine, S. Cotin

A method of template-based 3D recovery of elastic shapes using Lagrange multiplied was presented at a top computed-vision conference [21]. By exploiting the object's elasticity, in contrast to isometric methods that use inextensibility constraints, a large range of deformations can be handled. Our method is expressed as a saddle point problem using Lagrangian multipliers resulting in a linear system which unifies both mechanical and optical constraints and integrates Dirichlet boundary conditions, whether they are fixed or free. We experimentally show that no prior knowledge on material properties is needed, which exhibit the generic usability of our method with elastic and inelastic objects with different kinds of materials. Comparison with existing techniques are conducted on synthetic and real elastic objects with strains ranging from 25% to 130% resulting to low errors.

7.5. Simulation for Intra-operative Rehearsal

Participants: N. Haouchine, F. Roy, S. Cotin

DejaVu, a novel surgical simulation approach for intra-operative surgical gesture rehearsal was published in [22] in collaboration with UCL London. With DejaVu we aim at bridging the gap between pre-operative surgical simulation and crucial but not yet robust intra-operative surgical augmented reality. By exploiting intra-operative images we produce a simulation that faithfully matches the actual procedure without visual discrepancies and with an underlying physical modeling that performs real-time deformation of organs and surrounding tissues, surgeons can interact with the targeted organs through grasping, pulling or cutting to immediately rehearse their next gesture. We present results on different in vivo surgical procedures and demonstrate the feasibility of practical use of our system.

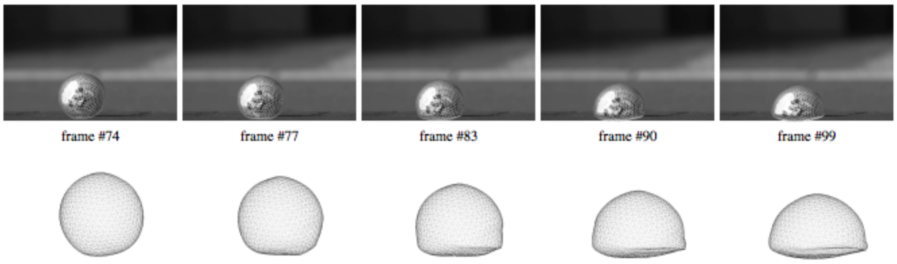

Figure 12. The proposed method illustrated on an example with a soft ball colliding the ground in slow motion. No prior knowledge of material properties in considered. The spherical volume model is composed of 512 linear P1 tetrahedral elements. The recovery and augmentation is performed in real-time at 25 FPS.

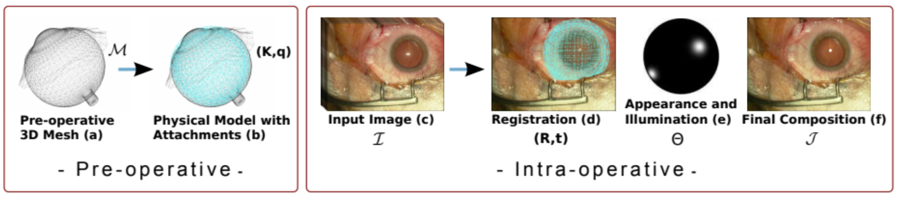

Figure 13. Schematic illustration of DejaVu Simulation. (a) preoperative model is built from tomographic images; (b) material law, tissue properties and attachments, constitute the physical model; (c) an intra-operative image is selected; (d) 3D/2D registration is performed between the physical model in (b) and the selected frame in (c); (e) appearance and illumination are estimated corresponding to specular and diffuse components and light position; (f) the final composition is build to enable surgical gesture rehearsal.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

MIMESIS has active bilateral collaborations with following industrial partners:

InSimo: A startup providing biomedical simulation software which are able to reproduce the behavior of organs, tissues and surgical procedures in a realistic and interactive way. Created in January 2013 as a spin-off forces by former members of team SHACRA (the predecessor of MIMESIS). Currently, we collaborate on simulations of eye surgery as well as on preparation of projects aiming at validation of algorithms and codes of simulation framework SOFA.

Altran: 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. We have a common history of successful collaboration via CIFRE Ph.D. thesis of Rosalie Plantefève. A new CIFRE Ph.D. will start on 01/01/2018 focusing on fusion of multisensor data in the context of intra-operative navigation of catheters.

Siemens: A global leader in healthcare industry. Via IHU, we collaborate with Siemens in the context of the IHU project *CIOS Alpha Fusion* dealing with augmentation of the intra-operative image provided by a fluoroscopic imaging modality with pre-operative data.

Renumics: A German startup focusing on automation of computer aided engineering (CAE) using artificial intelligence in general and machine learning techniques in particular. In close collaboration with SOFA Consortium, MIMESIS is involved in preparation of projects aiming at validation of SOFA.

Naviworks: A South Korean company specialized in ICT convergence simulation/IoT smart controlling. We collaborate on simulation and visualization in the context of interventional radiology.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. Institute of Image-Guided Surgery (IHU) Strasbourg

The Institute of Image-Guided Surgery of Strasbourg develops innovative surgery to deliver personalized patient care, combining the most advanced minimally invasive techniques and the latest medical imaging methods.

Project *CIOS Alpha Fusion* funded by IHU Strasbourg has started at the beginning of 2017. The goal of the project is to develop a solution for real-time, accurate, image fusion between 3D anatomical data and 2D X-ray images. This requires to spatially align these two imaging datasets with each other, knowing that a deformation has occurred between the 2 acquisitions. We consider two different cases, of increasing scientific complexity: static image fusion using 2 fluoroscopic images taken at 2 different angles, and dynamic image fusion using a single fluoroscopic image. We also consider two additional scenarios: in the first one, a 3D image or a 3D model has been obtained from a preoperative CTA or MRA while in the second scenario it has been acquired using an intra-operative contrast-enhanced CBCT. In the second case, tissue deformation between the 2D and 3D data is significantly reduced.

The project team involves scientists from the MIMESIS team at Inria, engineers from Siemens as industrial partner, and clinicians from the NHC hospital and IHU.

9.1.2. Research and Clinical Partners

At the regional level, the MIMESIS team collaborates with

ICube Automatique Vision et Robotique (AVR): We have been collaborating 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): MIMESIS 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 Hôpital Civil, Strasbourg: since 2014 we have been working with Prof. David Gaucher, an ophthalmologist and 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.

9.2. National Initiatives

9.2.1. ADT (Action de Développement Technologique)

Team MIMESIS received a support for the development of the SOFA framework through two ADTs:

DynMesh (Sep 2015 – Aug 2017): The objectives of the 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.

ASNAP (*Accélération des Simulations Numériques pour l'Assistance Peropératoire*, Jan 2017 – Dec 2018). We are partners of ADT ASNAP with principal investigator being Inria team CAMUS. The goal of the project is a significant acceleration of physics-based simulations developed by MIMESIS. The technologies such as Apollo, XFOR, ORWL, developed by team CAMUS are used to optimize the execution of different components of framework SOFA, taking into account the possibilities provided by modern CPUs and GPGPUs. Since team CAMUS is also located in Strasbourg, the project benefits from the geographical location: an engineer Maxim Mogé was recruited, starting from 01/01/2017 and he shares his time between the two teams.

9.2.2. ANR (Agence Nationale de la Recherche)

MIMESIS participates in the following ANR projects:

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. Retinal 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.

EVEREST: The overall objective of the EVEREST project is thus to bring a leap forward in factorization of large sparse tensors in order to improve the accessibility, completeness and reliability of real-world KBs. This line of research could have a huge impact in industry (Semantic Web, biomedical applications, etc.). For that reason, Xerox Research Center Europe is supporting this project and will supply data, provide expertise and ease industrial transfer. This proposal is also consistent with the long-term research direction of its principal partner, Heudiasyc, since it contributes in several aspects of the 10 years LabEx program on *Technological Systems of Systems* started in 2011.

Coordinator: IHU Strasbourg

Partners: Inria, IRCAD, University of Strasbourg, Siemens Healthcare, Karl Storz GmbH., University of Twente

9.2.3. Inria Collaborations

MIMESIS is closely connected to the SOFA Consortium, created by Inria in November 2015 with the objective to support the SOFA community and encourage contributions from new SOFA users. The Consortium should also be a way to better answer to the needs of academic or industrial partners. MIMESIS actively participates at the development of SOFA and contributed to the evolution of the framework. Moreover, MIMESIS also participates in an initiative aiming at verification and validation of codes and algorithms of SOFA.

Further, MIMESIS actively collaborates with the following Inria teams:

MAGRIT: The team at Inria Grand Est focuses on research in computer vision and is also actively involved in computer-based solutions for the planning or the simulation of interventional radiology procedures, with a strong collaboration with the CHU in Nancy. We collaborate with MAGRIT in the area of interventional radiology and augmented reality. Currently, two PhD thesis are co-supervised by researcher from Magrit: the PhD thesis of Jaime Garcia Guevara and Raffaella Trivisonne.

CAMUS: The team focuses 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 multi-core processors. Currently, we collaborate with team CAMUS on parallelization of framework SOFA in ADT project ASNAP.

DEFROST: The team conducts research in soft robotics. We continue mutual interaction with DEFROST mainly in the context of contact modeling.

9.2.4. National Collaborations

At the national level, the MIMESIS team collaborates with:

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.

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.

Hôpital Paul-Brousse: a hospital in South Paris. We collaborate with *Centre Hépato-Biliaire* via the co-supervision of the Ph.D. thesis of Nicolas Golse, MD, who is a surgeon at the center.

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

Program: H2020, Innovative Training Network, MSCA

Project acronym: HiPerNav

Project title: High performance soft tissue navigation

Coordinator: Oslo University Hospital

Other partners: SINTEF Trondheim, University of Bern

Abstract: HiPerNav is an Innovative Training Network (ITN) funded through a Marie Skłodowska-Curie grant. There will be 14 fully funded and 2 partially funded PhD's working on the project. The project aims to improve soft tissue navigation through research and development, to improve several bottleneck areas:

- Creating effective pre-operative model(s) and planning
- Faster and more accurate intra-operative model updates
- Faster and more accurate model-to-patient registration
- More intuitive user-interaction and effective work flow
- Usage of high performance computing (e.g. GPU)

9.3.2. Informal Collaborations

University of Twente: Thanks to our clinical partner IHU, we collaborate with Prof. Stefano Stramigioli, head of a group at Robotics and Mechatronics laboratory.

Faculty of Informatics, Masaryk University, Czech Republic: We collaborate on simulation of living cells in fluorescent microscopy. The collaboration resulted in a presentation at an international conference [29] and a journal paper [18].

Team Legato, University of Luxembourg: we have an active collaboration with Prof. Stéphane Bordas on error estimation in real-time simulations of deformable objects. The collaboration resulted in a common publication [16].

9.4. International Initiatives

The MIMESIS team actively collaborates with following international partners:

CIMIT & Harvard Medical School, Boston, USA: We collaborate on a project REBOASim in the contect of interventional radiology, , in particular the design and development of a hardware interface for tracking catheters and guidewires. The common DoD project REBOASim focuses on development of the physics-based models for catheter and guidewire motion, blood flow and graphical rendering towards a novel simulator for REBOA that will include physical vascular access, simulated passage of the IR instruments into the aorta with accompanying training/educational content, device withdrawal and closure: Duration of the project: Feb 2017 – Feb 2019.

9.5. International Research Visitors

9.5.1. Visits of International Scientists

From Feb 2017 to July 2017, **Prof. Adam Wittek** joined team MIMESIS as a visiting scientist. Prof. Wittek is with Intelligent Systems for Medicine Laboratory, School of Mechanical and Chemical Engineering at the University of Western Australia, Perth. His research focuses on patient-specific biomechanical modeling and he has published an important number of high-quality publications on this topic with more than 2,000 citations.

During his stay, Prof. Wittek provided his highly valuable expertise in various domains of patient-specific simulations and advanced techniques of modeling of deformations in soft tissues such as meshless methods. He was also involved in projects related to insertions of flexible needles into soft tissues.

9.5.1.1. Internships

From Jul 2017 to Dec 2017, Vincent Magnoux, a Canadian PhD student from École polytechnique de Montréal, joined MIMESIS as an international intern. During his stay, he has worked on implementing and validating a meshless method for computing organ deformation. This work also involved exploring methods to accelerate these computations on multi-core systems for an interactive simulation.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. Member of the Organizing Committees

David Cazier contributed to the organization of the Annual workshop of the *Animation & Simulation* group of the GDR IGRV of the CNRS in Strasbourg.

10.1.1.2. Reviewing Activities

Stephane Cotin provided reviews for: *Int. Conf. on Information Processing in Computer-Assisted Interventions, Workshop on Virtual Reality Interaction and Physical Simulation*

Igor Peterlik provided reviews for: *Int. Conf. of Medical Image Computing and Computer Assisted Intervention Society*

Antoine Petit provided reviews for: *International Conference on Robotics and Automation*

10.1.2. Journal

10.1.2.1. Reviewing Activities

Stephane Cotin provided reviews for: *International Journal of Computer Assisted Radiology and Surgery*

David Cazier provided reviews for: *Computer-Aided Design, Visual Computer, Computer & Graphics, Int. Journal on Virtual Reality*

Igor Peterlik provided reviews for: *Computer and Graphics*

Antoine Petit provided reviews for: *International Journal Of Robotics Research, Robotics and Automation Letters*

Christoph Paulus provided reviews for: *MDPI Journal Symmetry*

Lionel Untereiner provided reviews for: *Special Issue on Parallel and Distributed Algorithms of Concurrency and Computation*

10.1.3. Invited Talks

Keynote lecture by S. Cotin at 10th Medical Korea conference (Seoul, South Korea)

Invited lecture by S. Cotin FMTS conference (Strasbourg, France)

Invited lecture by S. Cotin B.E.S.T. symposium (Strasbourg, France)

Invited talk by S. Cotin at Fraunhofer MEVIS lab (Bremen, Germany)

Invited lecture by S. Cotin at European Computer-Assisted Liver Surgery Society (Mainz, Germany)

Invited lecture by S. Cotin at 127th annual meeting of the French Ophthalmology Association (Paris, France)

Invited lecture by S. Cotin at the French Academy of Surgery (Paris, France)

10.1.4. Scientific Expertise

Igor Peterlik has been providing a scientific expertise at Masaryk University, Czech Republic as a consultant and co-investigator of a project unded by Grant Agency of the Czech Republic: Development of Reliable Methods for Automated Quantitative Characterization of Cell Motility in Fluorescence Microscopy.

10.1.5. Research Administration

David Cazier is a member and local coordinator for a CITEPH project Paleo GTM: *A Paleo Geological and Topological Modeler*. Subject and expected contributions: multiresolution meshing and visualization for handling of massive geological data.

The project started in Sep 2017 (duration 2 years) and involves following partners:

- GEOSIRIS SAS (StartUp)
- Laboratoire ICUBE, UMR 7357 (Université de Strasbourg)
- Laboratoire XLIM, UMR 7352 (Université de Poitiers)
- Laboratoire LSIS, UMR 7296 (Université d'Aix-Marseille)

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Master: Igor Peterlik, Modélisation des systèmes vivants, 17h, M2, University of Strasbourg

Master: Igor Peterlik, Visualisation des données et simulation, 10h, M1, University of Strasbourg

Master: Hadrien Courtecuisse, Real time simulation, 30h, M2, University of Strasbourg

Master: Hadrien Courtecuisse, Visualisation des données et simulation, 10h, M2, University of Strasbourg

Master: Hadrien Courtecuisse, Visualisation des données et simulation, 10h, M1, University of Strasbourg

Licence: David Cazier, Web technologies and programming, 96h, L3, University of Strasbourg

10.2.2. Supervision

PhD: Christoph Paulus, *Modeling and real-time simulation of topological changes in soft tissue*, University of Strasbourg, 03/04/2017 [11]

PhD: Fanny Morin, *Non linear simulation for intra-operative guidance for neurosurgery*, Université Grenoble Alpes, 05/10/2017

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: Nicolas Golse, *Navigation using the augmented reality during hepatic surgery*, 01/09/2016, supervised by Stéphane Cotin

PhD in progress: Lukáš Ručka, *Validation and verification of soft tissue models*, 01/09/2016, co-supervised by Igor Peterlik, supervised by Prof. Ludek Matyska at Masaryk University, Czech Republic

PhD in progress: Sergei Nikolaev, *Characterization of boundary conditions for biomechanical modeling of liver*, 01/05/2017, supervised by Stéphane Cotin, co-supervised by Igor Peterlik and Hadrien Courtecuisse

PhD in progress: Jean-Nicolas Brunet, *Characterization of boundary conditions for biomechanical modeling of liver*, 01/09/2017, supervised by Stéphane Cotin

PhD in progress: Andrea Mendizabal, *Numerical simulation of soft tissues and machine learning*, 01/09/2017, supervised by Stéphane Cotin

10.2.3. Juries

Stéphane Cotin was a member of jury of HDR of Christian Herlin (MD): *Imagerie et simulation pour la chirurgie plastique et reconstructrice*. Université de Montpellier. Nov 2017

10.3. Popularization

Demonstration at *50 Years Inria* on Nov 10 in Paris, attended by Mr. Mounir Mahjoubi, secrétaire d'état auprès du premier ministre, chargé du numérique.

11. Bibliography

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[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.

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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

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2. Overall Objectives

2.1. Overall Objectives

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 [8], 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

5.1.1. Awards

Best student paper award at LTC'2017 (8th Language & Technology Conference) [39]

Third best paper award at ICNLSP'2017 (International Conference On Natural Language, Signal and Speech Processing) [42]

BEST PAPERS AWARDS :

[39] **LTC 2017 - 8th Language & Technology Conference**. A. HOUIDHEK, V. COLOTTE, Z. MNASRI, D. JOUVET, I. ZANGAR.

[42] **ICNLSSP'2017 - International Conference on Natural Language, Signal and Speech Processing**. D. JOUVET, D. LANGLOIS, M. A. MENACER, D. FOHR, O. MELLA, K. SMAÏLI.

6. New Software and Platforms

6.1. 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: Combines deep neural networks and multichannel signal processing for speech enhancement and separation of musical recordings.

NEWS OF THE YEAR: In 2017, we changed the type of multichannel filter used and modified the software so that it runs online in real time.

- Participants: Aditya Nugraha, Laurent Pierron, Emmanuel Vincent, Antoine Liutkus, Romain Serizel and Floris Fournier
- Contact: Emmanuel Vincent

6.2. 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 in French, English or Arabic. It is based on the Kaldi speech recognition tools. It relies on Deep Neural Network (DNN) modeling for speech detection and acoustic modeling of the phones (speech sounds). Higher order statistical language models and recurrent neural network language models can be used for improving performance through rescoring of multiple hypotheses.
NEWS OF THE YEAR: Better acoustic models have been developed for French, English and Arabic languages. An NN-based speech detection module has been included, as well as rescoring with RNN language models.

- Contact: Dominique Fohr

6.3. SOJA

Speech Synthesis platform in JAva
KEYWORDS: Speech Synthesis - Audio
SCIENTIFIC DESCRIPTION: SOJA relies on a non uniform unit selection algorithm. Phonetic and linguistic features are extracted and computed from the text to drive selection of speech units in a recorded corpus. The selected units are concatenated to obtain the speech signal corresponding to the input text.
FUNCTIONAL DESCRIPTION: SOJA is a software for Text-To-Speech synthesis (TTS). 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.
NEWS OF THE YEAR: SOJA now supports the unit selection with emotion tags.

- Participants: Alexandre Lafosse and Vincent Colotte
- Contact: Vincent Colotte

6.4. Xarticulators

KEYWORD: Medical imaging
FUNCTIONAL DESCRIPTION: The Xarticulators software is intended to delineate contours of speech articulators in X-ray and MR 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 or MR 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 2D-MRI films, and on the construction of better articulatory models for the velum, lips and epiglottis.
NEWS OF THE YEAR: New models of the lips, velum and epiglottis have been added. Xarticulators generates area functions from an MRI film annotated in terms of articulators.

- Contact: Yves Laprie
- Publication: Articulatory model of the epiglottis

6.5. Platforms

6.5.1. Platform MultiMod: Multimodal Acquisition Data Platform

We have set up an acquisition hardware platform to acquire multimodal data in speech communication context. The system was previously composed of the articulograph Carstens AG501 (which was acquired as part of the EQUIPEX ORTOLANG), 4 Vicon cameras (a motion capture system), and an Intel RealSense camera which contains four components: a video camera, an infrared laser projector, an infrared camera, and a microphone array. 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, we have replaced the 4 Vicon cameras by 8 optitrack cameras. The new motion capture system allows acquiring higher spatial and temporal resolution data, and allows faster acquisition and processing.

We are currently using the system to acquire expressive audiovisual data to build an expressive audiovisual speech synthesis in addition to a lipsync system.

- 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: Anne Bonneau, Vincent Colotte, Yves Laprie, Slim Ouni, Agnès Piquard-Kipffer, Benjamin Elie, Theo Biasutto-Lervat, Sara Dahmani, Ioannis Douros, Valérian Girard, Yang Liu, Anastasiia Tsukanova.

7.1.1. Articulatory modeling

7.1.1.1. Articulatory models and synthesis

The geometry of the vocal tract is essential to guarantee the success of articulatory synthesis. This year we worked on the construction of an articulatory model of the epiglottis from MRI images and X-ray films. The new model takes into account the influences of the mandible, tongue and larynx via a multi-linear regression applied to the contours of the epiglottis [44]. Once these influences are removed from the contours, principle component analysis is applied to the control points of the B-spline representing the centerline of the epiglottis. The main advantage of using the centerline is to reduce the effect of delineation errors. Following the same idea, we also developed an articulatory model of the velum.

Geometry of the vocal tract is an input of articulatory synthesis and an algorithm for controlling the positions of speech articulators (jaw, tongue, lips, velum, larynx and epiglottis) is required to produce given speech sounds, syllables and phrases. This control has to take into account coarticulation and be flexible enough to be able to vary strategies for speech production [65]. The data for the algorithm are 97 static MRI images capturing the articulation of French vowels and blocked consonant-vowel syllables. The results of this synthesis are evaluated visually, acoustically and perceptually, and the problems encountered are broken down by their origin: the dataset, its modeling, the algorithm for managing the vocal tract shapes, their translation to the area functions, and the acoustic simulation.

7.1.1.2. Acoustic simulations

The acquisition of EPGG data (ElectroPhotoGlottoGraphy) data in collaboration with LPP in Paris has allowed the exploration of the production of voiced and unvoiced fricatives with realistic glottis opening profiles. These data show that the glottal opening is gradual and starts well before the fricative itself. Production of fricatives were studied by using acoustic simulations based on classic lumped circuit element methods to compute the propagation of the acoustic wave along the vocal tract. The glottis model incorporating a glottal chink developed last year is connected to the wave solver to simulate a partial abduction of the vocal folds during their self-oscillating cycles. Area functions of fricatives at the three places of articulation of French (palato-alveolar, alveolar, and labiodental) have been extracted from static MRI acquisitions. Simulations highlight the existence of three distinct regimes, named A, B, and C, depending on the degree of abduction of the glottis. They are characterized by the frication noise level: A exhibits a voiced signal with a low frication noise level, B is a mixed noise/voiced signal, and C contains only frication noise [33], [12].

Following the same approach of coupling articulatory data and acoustic simulation we investigated the acoustic simulation of alveolar trills, and the articulatory and phonatory configurations that are required to produce them. Using a realistic geometry of the vocal tract, derived from cineMRI data of a real speaker, the mechanical behavior of a lumped two-mass model of the tongue tip was studied [13]. The incomplete occlusion of the vocal tract during linguopalatal contacts was modeled by adding a lateral acoustic waveguide. Finally, the simulation framework is used to study the impact of a set of parameters on the characteristic features of the produced alveolar trills. It shows that the production of trills is favored when the tongue tip position is slightly away of the alveolar zone, and when the glottis is fully adducted.

7.1.1.3. Acquisition of articulatory data

The effort of acquiring new articulatory data was quite strong this year: **(i)** acquisition of MRI films (136 x 136 pixel images at a sampling rate of 55Hz) of continuous speech in Max Planck Institute Göttingen with Prof. Jens Frahm. We collected 2 hours of speech for 2 male speakers covering sentences and spontaneous speech. The sentences were designed so as to contain all the consonants and consonant clusters (excepted the very rare ones) in four vocalic contexts (the three cardinal vowels and /y/) and some intermediate vowels to check how they can be derived from those extreme vowels. The acoustic speech signal was recorded and denoised. Orthographic annotations of speech are available and the phonetic alignments were computed from the denoised speech signal. **(ii)** acquisition of EPGG (ElectroPhotoGlottoGraphy) data in LPP (Laboratoire de Phonologie et de Phonétique in Paris). The principle is to measure the flow of light (infrared light) which crosses the glottis. The emitting source is placed above the glottis and a light sensor below. The flow of light crossing the obstacle is roughly proportional to the surface of the glottis. Data acquired cover VCVs for fricatives and stops and some consonant clusters. These data were used to study the coordination between glottis opening and the realization of constrictions in the vocal tract. **(iii)** acquisition of fibroscopy data in HEGP (Georges Pompidou European Hospital). The principle is to introduce a smooth endoscope through the nostrils up to the top of the pharynx so as to image the glottis opening. This technique only allows a frequency close to 50 Hz which is not sufficient to observe the smooth glottis opening profiles accompanying the production of fricatives. Data have been collected for one female speaker and two male speakers.

7.1.2. Expressive acoustic and visual synthesis

We have improved our audiovisual acquisition techniques by acquiring a very advanced 8-camera motion capture system that allows capturing 3D data with higher temporal resolution and accuracy. We have acquired a small corpus for testing and evaluation purpose.

Within the framework expressive audiovisual speech synthesis, a perceptive case study on the quality of the expressiveness of a set of emotions acted by a semi-professional actor has been conducted. We have analyzed the production of this actor pronouncing a set of sentences with acted emotions, during a human emotion-recognition task. We have observed different modalities: audio, real video, 3D-extracted data, as unimodal presentations and bimodal presentations (with audio). The results of this study show the necessity of such perceptive evaluation prior to further exploitation of the data for the synthesis system. The comparison of the modalities shows clearly what the emotions are, that need to be improved during production and how audio and visual components have a strong mutual influence on emotional perception [57].

7.1.3. Categorization of sounds and prosody for native and non-native speech

7.1.3.1. Categorization of sounds for native speech

Concerning the mother tongue, we conducted empirical research. We followed 170 young people, aged from 6 to 20 years old, with langage deficiencies - dyslexia and Specific Language Impairment (SLI) - including categorization of sounds. We examined the links between those difficulties and their schooling experience and observed how they constituted a point of major obstacle at the time of learning to read and to write, which the pupils do not overcome. All of them were in a handicap situation [18].

We conducted two descriptive studies which aims were to give an overview of educational systems for students with special educational needs, including pupils with learning and sound categorization disabilities (LD). Around the world, schooling is different from one country to another, according to the languages, even every country follows the international movement of school for all. For these students, the question of the best mode of inclusion remains topical [16]. In France, different types of scooling are observed. We focused our study on a particular system of teaching - a local unit for inclusive education - for children aged from 6 to 12 with specific language disorders - dyslexia and SLI - and learning disabilities, in a specialised school. We described a few exemples of pedagogical multimodal accomodations [15].

7.1.3.2. Digital books for language impaired children

In the framework of Handicom ADT project [7], we used one of the digital books prototypes set up with the use of a 3D avatar as narrator and multimodal speech, combining oral, written language and visual clues (i.e. LPC, french cued speech), specially targeting children between 3 and 6. After the study conducted with digital album users, speech-therapists or re-eductors with hearing impaired impaired children, SLI and children with autism [81], we conducted another study, following children at school to investigate how technological innovations could help kindergarten children's (with and without langage difficulties) to improve their speech and language habilities.

7.1.3.3. Analysis of non-native pronunciations

Deviations in L2 intonation affect a number of prosodic characteristics including pitch range, declination line, or the rises of non-final intonation phrases, and might lead to misunderstandings or contribute to the perception of foreign-accent. This study investigates the characteristics of non-native speech at the boundary between prosodic constituents [67]. We analyzed a French declarative sentence, extracted from the IFCASL corpus (http://www.ifcasl.org), made up of four constituents and pronounced with a neutral intonation. Each constituent has three syllables and the sentence is realized typically by French speakers with four accentual –prosodic- groups, corresponding to the four constituents. Fourty German learners of French (beginners, and advanced speakers) and fifty four French speakers read the sentence once. We used the software ProsodyPro from Yi Xu for the prosodic analysis. We determined the presence of pauses and evaluated for each prosodic group: the (normalized) F0 maximum on the last syllable; the F0 excursion (max-min) of the final contour, and its maximum of velocity. In order to analyze the temporal course of F0 on the final contour, we also compared the values of the F0 excursion on the vowel and before it. On the basis of acoustic cues, non-native speakers, especially beginners, appear to realize more important prosodic boundaries (in particular higher F0 maxima, especially at the very end of the prosodic group, and more pauses) than French speakers, whereas native speakers appear to show more anticipation.

7.2. Statistical Modeling of Speech

Participants: Vincent Colotte, Dominique Fohr, Irène Illina, Denis Jouvet, Antoine Liutkus, Odile Mella, Romain Serizel, Emmanuel Vincent, Md Sahidullah, Guillaume Carbajal, Ken Deguernel, Mathieu Fontaine, Amal Houidhek, Aditya Nugraha, Laureline Perotin, Imran Sheikh, Sunit Sivasankaran, Ziteng Wang, Ismaël Bada.

7.2.1. Source separation

We wrote an extensive overview article about multichannel source separation and speech enhancement [14] and two book chapters about single-channel [72] and multichannel separation based on nonnegative matrix factorization [74].

7.2.1.1. Deep neural models for source separation and echo suppression

We pursued our research on the use of deep learning for multichannel source separation. In our previous work, which we summarized in a book chapter [73], we estimated the short-time spectra of the sound sources by a deep neural network and their spatial covariance matrices by a classical expectation-maximization (EM) algorithm and we derived the source signals by a multichannel Wiener filter. We also explored several variants of the multichannel Wiener filter, which turned out to result in better speech recognition performance on the CHiME-3 dataset [23]. We developed a new "end-to-end" approach which estimates both the short-time spectra and the spatial covariance matrices by a dedicated deep neural network architecture and which outperforms previously proposed approaches on CHiME-3. Arie Aditya Nugraha described the latter approach in his thesis, which he successfully defended. We started exploring the usage of deep neural networks for reducing the residual nonlinear echo after linear acoustic echo cancellation [80] and for separating multiple speakers from each other.

We also continued our work on music source separation, with the organization of the successful Signal Separation Evaluation Challenge (SiSEC 2016 [46]), as well as with national and international collaborations on this topic [34], [47], [58], [59], [60]. This research activity features several important research directions, described below.

7.2.1.2. Alpha-stable modeling of audio signals

Under the KAMoulox funding, we investigated the use of alpha-stable probabilistic models for source separation. As opposed to their more classical counterparts, these models feature very heavy tails, which allows to better account for the large dynamics found in audio signals. In close collaboration with national and international partners, we published several papers in international conferences on these topics. We demonstrated that alpha-stable processes allow to understand long-standing practices in speech enhancement [36]. More specifically, we showed that parameterized Wiener filters, dating back to the early 80s, can be understood as the optimal filtering strategy when sources are distributed with respect to alpha-stable distributions of different characteristic exponents. Interestingly, this gives a rationale for setting filtering parameters that were always manually tuned. Stable distributions also allow generalizing Wiener filtering for nonnegative sources [48], [49], and are interesting for robust multichannel separation [45], in the sense that they permit to compensate for model mismatch efficiently.

7.2.1.3. Scalable source localization

In the context of KAMoulox, we studied how probabilistic modeling of multichannel audio with alpha-stable distributions leads to models for microphone arrays that allow for scalable inference for the source positions [37], [38]. The core points of these methods are twofold. First, heaviness of the tails of alpha-stable distributions allows to efficiently model the marginal distribution of sources spectra. This is in sharp contrast with Gaussian distributions, that can only correctly represent audio signals adequately if each time-frequency point has its own distribution. On the contrary, while alpha-stable distributions give a high probability mass to small magnitudes, they also allow for the important deviations to be expected when the source is active. The advantage of such a model for marginal distributions over the whole time-frequency plane is to dramatically reduce the number of parameters and thus lead to much robust estimation methods. The second innovation brought in by the proposed localization method is to compute a summarized representation of the data, and to proceed to inference on this representation instead of using the -massive- original data.

7.2.1.4. Interference reduction

Under the DYCI2 schedule, we significantly extended our previous research on interference reduction for musical recordings. This task consists in reducing inter-microphone leakage in live recordings and has many applications in the audio engineering industry. This lead us to propose two important contributions on this respect. First, we amended previous methods to correctly exploit the proposed probabilistic model: previous research indeed featured some ad-hoc and suboptimal steps. This was corrected and the corresponding extension proved to behave much better [30]. Second, we investigated whether the proposed methods can be generalized to process full-length recordings. This is indeed an important and challenging question, because full-length multitrack recordings are extremely large and cannot reasonably be processed with current methods. This line of research lead us to propose inferring some parameters on compressed representations, which is promising ongoing research.

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. We conducted an extensive evaluation of several approaches for speech recognition in varied reverberation conditions, including both established and newly proposed approaches [21].

Speech enhancement and automatic speech recognition (ASR) are most often evaluated in matched (or multicondition) 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 [22]. The results show that multi-condition training outperforms matched training on average, but training on a subset of noise environments only is preferable in a few specific cases [25]. This raises the question: what are the optimal training conditions given the task to be solved, the deep neural network architecture, and the test conditions? We provided a preliminary answer to this question by means of a discriminative importance weighting algorithm which aims to select the most useful training data in a rigorous optimization framework [64].

In order to motivate further work by the community, we created the series of CHiME Speech Separation and Recognition Challenges in 2011. Following the organization of the CHiME-3 Challenge in 2015, we edited a special issue [9] of *Computer Speech and Language*, which includes a detailed description of its outcomes [10]. We also published a book chapter that summarizes the outcomes of the whole series of challenges [70].

7.2.2.2. Environmental sounds

Following the recruitment of Romain Serizel in Fall 2016, our team has become more involved in the community on environmental sound recognition. In collaboration with Carnegie Mellon University (USA), we co-organized the first ever large-scale environmental sound recognition evaluation. This evaluation relied on the Audioset corpus released by Google and was part of the DCASE 2017 Challenge [24]. It focused on the problem of learning from weak labels for an application to smart cars.

We continued our work on acoustic scene classification. In particular, we focused on exploiting matrix factorization techniques for features learning. We extended previous work that used these learned features as an input to a linear classifier [11] to the deep learning framework [27], [28] and we proposed to jointly learn the deep-learning based classifier and the dictionary matrix [27]. A system based on this approach was submitted to DCASE challenge and was among the top 25% systems [28].

7.2.2.3. Speech/Non-speech detection

Automatic Speech Recognition (ASR) of multimedia content such as videos or multi-genre broadcasting requires a correct extraction of speech segments. We explored the efficiency of deep neural models for speech/non-speech segmentation. The first results, achieved in the MGB Challenge framework, show an improvement of the ASR word error rate compared to a Gaussian Mixture Model (GMM) based speech/non-speech segmenter.

7.2.2.4. Data selection

Training a speech recognition system needs audio data and their corresponding exact transcriptions. However, manual transcribing is expensive, labor intensive and error-prone. Some sources, such as TV broadcast, have subtitles. Subtitles are closed to the exact transcription, but not exactly the same. Some sentences might be paraphrased, deleted, changed in word order, etc. Building automatic speech recognition from inexact subtitles may result in a poor model and low performance system. Therefore, selecting data is crucial to obtain highly efficient models. We study data selection methods based on phone matched error rate and average word duration [26]

7.2.2.5. Transcription systems

We designed a new automatic transcription system based on deep learning with an acoustic modeling done by TDNN-HMM and a language model rescoring using RNN. In the framework of the AMIS project, we developped automatic systems for the transcription of TV shows in English, in French and in Arabic [52] [51].

7.2.2.6. Speaker identification

We proposed supervised feature learning approaches for speaker identification that rely on nonnegative matrix factorization [61]. The approach integrates a recent method that relies on group nonnegative matrix factorization into a task-driven supervised framework for speaker identification [11]. The goal is to capture both the speaker variability and the session variability while exploiting the discriminative learning aspect of the task-driven approach.

7.2.3. Language 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. We proposed a Neural Bag-of-Weighted Words (NBOW2) model which learns to assign higher weights to words that are important for retrieval of an OOV PN. [20]. We explored topic segmentation in ASR transcripts using bidirectional RNNs for change detection [62].

7.2.3.2. Adding words in a language model

We proposes new approaches to OOV proper noun probability estimation using Recurrent Neural Network Language Model (RNNLM). The proposed approaches are based on the notion of closest in-vocabulary words (list of brothers) to a given OOV proper noun. The probabilities of these words are used to estimate the probabilities of OOV proper nouns thanks to RNNLM [40].

7.2.3.3. Updating speech recognition vocabularies

In the framework of the AMIS project, the update of speech recognition vocabularies has been investigated using web data collected over a time period similar to that of the collected videos, for three languages: French, English and Arabic [42]. Results shows that a significant reduction of the amount of out-of-vocabulary words is observed for the three languages, and that, for a given vocabulary size, the percentage of out-of-vocabulary words is higher for Arabic than for the other languages.

7.2.3.4. Segmentation and classification of opinions

Automatic opinion/sentiment analysis is essential for analysing large amounts of text as well as audio/video data communicated by users. This analysis provides highly valuable information to companies, government and other entities, who want to understand the likes, dislikes and feedback of the users and people in general. We proposed a recurrent neural network model with bi-directional LSTM-RNN, to perform joint segmentation and classification of opinions [63].

7.2.3.5. 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 [79]. In the context of ANR DYCI2, we described a general framework for automatic music improvisation that encompasses three existing paradigms [56] and that relies on our previous work about combining a multi-dimensional probabilistic model encoding the musical experience of the system and a factor oracle encoding the local context of the improvisation. Inspired in particular by the regularity of the temporal structure of popular music pieces [19], we proposed a new polyphonic music improvisation approach that takes the structure of the musical piece at multiple time scales into account [32].

7.2.4. Speech generation

Work on Arabic speech synthesis was carried out within a CMCU PHC project with ENIT (École Nationale d'Ingénieurs de Tunis, Tunisia, cf. 9.4.2.1), using HMM and NN based approaches applied to Modern Standard Arabic language.

HMM-based speech synthesis system relies on a description of speech segments corresponding to phonemes, with a large set of features that represent phonetic, phonologic, linguistic and contextual aspects. When applied to Modern Standard Arabic, two specific phenomena have to be taken in account, the vowel quantity and the consonant gemination. This year, we studied thoroughly the modeling of these phenomena. Results of objective and subjective evaluations showed that the results are similar between the different approaches that have been studied [39]. Other similar experiments are on-going using neural-network-based synthesis.

A particular weakness point of HMM-based synthesis quality may be due to the prediction of prosodic features which is based on a decision tree approach. Neural network are known for their ability to model complex relationships. This year, we studied the modeling of phoneme duration with NN approaches. Predicted phoneme durations will then be included in the Modern Standard Arabic synthesis system.

In parallel, the neural network based approach has also been tested on the French language.

7.3. Uncertainty Estimation and Exploitation in Speech Processing

Participants: Vincent Colotte, Dominique Fohr, Denis Jouvet, Yves Laprie, Odile Mella, Emmanuel Vincent, Yassine Boudi, Mathieu Hu, Karan Nathwani.

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 and propagate it through the acoustic model for robust ASR. We conducted an extensive experimental investigation of existing uncertainty estimation and propagation techniques using deep neural network acoustic models on two different datasets (CHiME-2 and CHiME-3) [53]. We also proposed a deep neural network-based uncertainty estimator and a consistent way of accounting for uncertainty in both the training and decoding stage [54]. Overall, we were the first to report a significant improvement using uncertainty estimation and propagation compared to a competitive deep neural network acoustic modeling baseline based on feature-domain maximum likelihood linear regression (fMLLR) features.

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 [55]. In his successfully defended thesis, Quan Van Nguyen also described a way of locating multiple sources. 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 [31].

7.3.2. Uncertainty and phonetic segmentation

In the framework of the LCHN CPER project (cf. 9.1.1), for studying prosodic correlates of discourse particles in French, phonetic boundaries of discourse particles and adjacent words have been checked and manually corrected; this shows that there is still a need for performance improvement of the automatic speech-text alignment process.

We also worked on speech-to-speech alignement, with the goal of obtaining a precise alignement between two speakers pronouncing the same sentence. This task is difficult due to the fact that the speakers may pronounce certain sounds in a different way, or they may insert or remove silences between words. We introduced explicit phoneme duration and insertion/deletion models for alignment and evaluated them on real data.

7.3.3. Uncertainty and prosody

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 [43]. A first set of experiments have been conducted for computing a confidence measure on the estimated F0 values through the use of neural network approaches [29].

Study of discourse particles in French has continued thanks to the support of the CPER LCHN project. So far a few French words frequently used as discourse particles have been studied. Several thousands occurrences have been extracted from the ESTER and the ORFEO speech corpora, and annotated as discourse particle or not. The pragmatic function of the discourse particles has also been annotated. Prosodic correlates of these words have been analyzed with respect to their function (discourse particle or not, as well as pragmatic function) [66], and some automatic classification processes have been investigated [41].

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. Orange

Company: Orange SA (France)
Duration: Nov 2016 – Nov 2019
Participants: Laureline Perotin, Romain Serizel, Emmanuel Vincent
Abstract: This CIFRE contract funds the PhD thesis of Laureline Perotin with Orange Labs. Our goal is to develop deep learning based speaker localization and speech enhancement algorithms for robust hands-free voice command. We are especially targetting difficult scenarios involving several simultaneous speakers.

8.1.2. Invoxia

Company: Invoxia SAS (France)
Duration: Mar 2017 – Mar 2020
Participants: Guillaume Carbajal, Romain Serizel, Emmanuel Vincent
Abstract: This CIFRE contract funds the PhD thesis of Guillaume Carbajal. Our goal is to design a unified end-to-end deep learning based speech enhancement system that integrates all steps in the current speech enhancement chain (acoustic echo cancellation and suppression, dereverberation, and denoising) for improved hands-free voice communication.

8.1.3. Studio Maia

Company: Studio Maia SARL (France)
Other partners: Imaging Factory
Duration: Jul 2017 – Dec 2018
Participants: Yassine Boudi, Vincent Colotte, Mathieu Hu, Emmanuel Vincent
Abstract: This Inria Innovation Lab aims to develop a software suite for voice processing in the multimedia creation chain. The software is aimed at sound engineers and it will rely on the team's expertise in speech enhancement, robust speech and speaker recognition, and speech synthesis.

8.1.4. Samsung

Company: Samsung Electronics Co., Ltd (South Korea)
Duration: Jan – Nov 2017
Participants: Aditya Nugraha, Romain Serizel, Emmanuel Vincent
Abstract: This project aimed to transfer a modified version of dnnsep for hands-free voice command applications. We changed the type of multichannel filter used and modified the software so that it runs online in real time.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. CPER LCHN

Project acronym: CPER LCHN
Project title: CPER "Langues, Connaissances et Humanités Numériques"
Duration: 2015-2020
Coordinator: Bruno Guillaume (LORIA) & Alain Polguère (ATILF)
Participants: Dominique Fohr, Denis Jouvet, Odile Mella, Yves Laprie
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. This year we have also developped a complete system for the transcription of English broadcast TV shows to participate to the MGB challenge.

9.1.2. CPER IT2MP

Project acronym: CPER IT2MP

Project title: CPER “Innovation Technologique Modélisation et Médecine Personalisée”

Duration: 2015-2020

Coordinator: Faiez Zannad (Inserm-CHU-UL)

Participants: Romain Serizel, Vishnu Varanasi, Emmanuel Vincent

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.

9.1.3. Dynalips

Project title: Control of the movements of the lips in the context of facial animation for an intelligible lipsync.

Duration: February 2017 - January 2018

Coordinator: Slim Ouni

Participants: Valerian Girard, Slim Ouni

Funding: SATT

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. 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.

Participants: Theo Biasutto-Lervat, Anne Bonneau, Vincent Colotte, Dominique Fohr, Denis Jouvet, Odile Mella, Slim Ouni

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.

9.2.2. PIA2 ISITE LUE

Project acronym: ISITE LUE

Project title: Lorraine Université d'Excellence

Duration: starting in 2016

Coordinator: Univ. Lorraine

Participants: Ioannis Douros, Yves Laprie

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.

9.2.3. 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

Participants: Dominique Fohr, Irina Illina, Denis Jouvet, Odile Mella, Imran Sheikh

Abstract: The ContNomina project was focus 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 has addressed 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).

MULTISPEECH contributes to speech recognition and proper names handling (prediction, introduction in models, ...)

9.2.4. ANR DYCI2

Project acronym: DYCI2 (http://repmus.ircam.fr/dyci2/)

Project title: Creative Dynamics of Improvised Interaction

Duration: March 2015 - February 2018

Coordinator: Ircam (Paris)

Other partners: Inria (Nancy), University of La Rochelle

Participants: Ken Deguernel, Nathan Libermann, Emmanuel Vincent

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.

MULTISPEECH is responsible for designing a system able to improvise on multiple musical dimensions (melody, harmony) across multiple time scales.

9.2.5. 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

Participants: Mathieu Fontaine, Antoine Liutkus

Abstract: The objective is to 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.

9.2.6. 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)

Participants: Ioannis Douros, Benjamin Elie, Yves Laprie, Anastasiia Tsukanova

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.

Acquisition and processing of cineMRI, new developments of acoustic simulations concercing the production of fricatives and trills, and first workds in the implementation of coarticulation in articulatory synthesis are the main activities of this year.

9.2.7. ANR VOCADOM

Project acronym: VOCADOM (http://vocadom.imag.fr/)

Project title: Robust voice command adapted to the user and to the context for AAL

Duration: January 2017 - December 2020

Coordinator: CNRS - LIG (Grenoble)

Other partners: Inria (Nancy), Univ. Lyon 2 - GREPS, THEORIS (Paris)

Participants: Dominique Fohr, Sunit Sivasankaran, Emmanuel Vincent

Abstract: The goal of this project is to design a robust voice control system for smart home applications. We are responsible for the speech enhancement and robust automatic speech recognition bricks.

MULTISPEECH is responsible for wake-up word detection, overlapping speech separation, and speaker recognition.

9.2.8. FUI VoiceHome

Project acronym: VoiceHome

Duration: February 2015 - July 2017

Coordinator: VoiceBox Tachnologies France

Other partners: Orange, Delta Dore, Technicolor Connected Home, eSoftThings, Inria (Nancy), IRISA, LOUSTIC

Participants: Irina Illina, Karan Nathwani, Emmanuel Vincent

Abstract: The goal of this project was to design a robust voice control system for smart home and multimedia applications. We were responsible for the robust automatic speech recognition brick.

MULTISPEECH was responsible for robust automatic speech recognition by means of speech enhancement and uncertainty propagation.

9.2.9. MODALISA

Project acronym: MODALISA

Project title: Multimodality during Language Acquisition: Interaction between Speech Signal and gestures

Duration: January 2017 - December 2017

Coordinator: Christelle Dodane (Praxiling, UMR 5267, Montpellier)

Other partners: Slim Ouni

Participants: Slim Ouni

Funding: CNRS DEFI Instrumentation aux limites

Abstract: The objective of this project was to setup a multimodal platform allowing simultaneous visualization of gestural (motion capture system) and prosodic data during speech and more specifically during language acquisition.

Les contributions de MULTISPEECH concernent l'acquisition et le traitement des données multimodales grâce à la plateforme multimodale MultiMod.

9.3. European Initiatives

9.3.1. Collaborations in European Programs, Except FP7 & H2020

9.3.1.1. AMIS

Program: CHIST-ERA

Project acronym: AMIS

Project title: Access Multilingual Information opinionS

Duration: Dec 2015- Nov 2018

Coordinator: Kamel Smaïli

Other partners: University of Avignon, University of Science and Technology Krakow, University of DEUSTO (Bilbao)

Participants: Dominique Fohr, Denis Jouvet, Odile Mella

Abstract: The idea of the project is to develop a multilingual help system of understanding without any human being intervention. What the project would like to do, is to help people understanding broadcasting news, presented in a foreign language and to compare it to the corresponding one available in the mother tongue of the user.

MULTISPEECH contributions concern mainly the speech recognition in French, English and Arabic videos.

9.3.2. Collaborations with Major European Organizations

Jon Barker: University of Sheffield (UK)

Robust speech recognition [22], [10], [9], [70]

9.4. International Initiatives

9.4.1. Inria International Partners

9.4.1.1. Informal International Partners

Shinji Watanabe, Johns Hopkins University (USA)

Robust speech recognition [22], [10], [9], [70]

9.4.2. Participation in Other International Programs

9.4.2.1. PHC UTIQUE - Arabic speech synthesis

PHC UTIQUE - Arabic speech synthesis, with ENIT (École Nationale d'Ingénieurs de Tunis, Tunisia)

Duration: 2015 - 2018.

Coordinators: Vincent Colotte (France) and Zied LACHIRI (Tunisia).

Participants: Vincent Colotte, Amal Houidhek, Denis Jouvet

Abstract: Modeling of a speech synthesis system for the Arabic language. This includes the use of an Arabic speech corpus, the selection of linguistic features relevant to an Arabic speech synthesis, as well as improving the quality of the speech signal generated by the system (prosodic and acoustic features).

MULTISPEECH co-supervises PhD students.

9.4.2.2. FIRAH - La famille face au handicap

Program: FIRAH, International Foundation of Applied Disability Research

Project title: La famille face au handicap : la gestion du stress parental des parents d'enfants souffrant du syndrome de Dravet

Duration: Jan 2017- Dec 2019

Coordinator: T. Leonova, University of Lorraine (Perseus)

Other partners: MHS-USR 3261 CNRS, Université de Lorraine, Associations Alliance Syndrome de Dravet (France) and Alliance Syndrome de Dravet (Suisse), Hopital de Hautepierre - Strasbourg University (France), Hopital Necker enfants malades - Paris Descartes University - INSERM U1129, Hôpital Robert Debré - Paris Diderot University- INSERM U1141, Hôpitaux Universitaires de Genève - Université de Genève (Suisse), Université catholique du Sacré Cœur - Rome (Italie), Quebec University (Canada), McMaster Children's Hospital - McMaster University - Hamilton (Canada), MIA518-AgroParisTech/INRA.

Participant: Agnès Piquard-Kipffer

Abstract: the aims of the project are, in a first step, to explore parental stress with Chidren with Dravet syndrom which combine infant epilepsy and autism and in a second step to create a training programm for professionnals of Education [68], [69]

In this project, MULTISPEECH is involved in finding the best ways to maximize the communication efficiency between the children and their families, using the methodology or the tools created by the Handicom project.

9.5. International Research Visitors

9.5.1. Visits of International Scientists

Ziteng Wang

Date: Sep 2016 – Sep 2017

Institution: Institute of Acoustics, Chinese Academy of Sciences (China)

Vishnuvardhan Varanasi

Date: Feb – Aug 2017

Institution: Indian Institute of Science, Kanpur (India)

Md Sahidullah

Date: Aug – Oct 2017

Institution: University of Eastern Finland (Finland)

9.5.2. Visits to International Teams

9.5.2.1. Research Stays Abroad

Antoine Liutkus was invited by Kazuyoshi Yoshii (RIKEN, Kyoto University) to work on multichannel extensions to his tensor-factorization methods, that would also allow for much easier inference. This led to a joint publication [47] about the resulting method.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

Elected chair, Steering Committee of the Latent Variable Analysis and Signal Separation (LVA/ICA) conference series (E. Vincent)

General co-chair, AVSP 2017 - 14th International Conference on Auditory-Visual Speech Processing (S. Ouni)

10.1.1.2. Member of the Organizing Committees

Co-organizer of the Task “Large-scale weakly supervised sound event detection for smart cars”, DCASE 2017 Challenge on Detection and Classification of Acoustic Scenes and Events (E. Vincent)

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)

Co-organizer of AVSP 2017 - International Conference on Auditory-Visual Speech Processing (S. Ouni)

10.1.2. Scientific Events Selection

10.1.2.1. Chair of Conference Program Committees

Program chair, DCASE 2017 Workshop on Detection and Classification of Acoustic Scenes and Events (E. Vincent)

Review chair, IEEE Technical Committee on Audio and Acoustic Signal Processing, responsible for organizing the review of the 313 papers submitted to the 2018 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP) in the general AASP domain (E. Vincent)

Proceedings co-chair (editor), AVSP 2017 - 14th International Conference on Auditory-Visual Speech Processing [76] (S. Ouni)

10.1.2.2. Member of the Conference Program Committees

AVSP 2017 - 14th International Conference on Auditory-Visual Speech Processing (S. Ouni)

ICNLSSP'2017 - International Conference on Natural Language, Signal and Speech Processing (D. Fohr, D. Jouvet, O. Mella)

Area chair, 2017 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA) (E. Vincent)

ISSP 2017 - International Seminar On Speech Production (Y. Laprie)

10.1.2.3. Reviewer

ASRU'2017 - IEEE Automatic Speech Recognition and Understanding Workshop (D. Jouvet, I. Illina, E. Vincent)

AVSP 2017 - 14th International Conference on Auditory-Visual Speech Processing (S. Ouni)

DCASE'2017 - Workshop on Detection and Classification of Acoustic Scenes and Events (R. Serizel, E. Vincent)

EUSIPCO'2017 - European Signal Processing Conference (D. Jouvet, A. Liutkus)

GLU'2017 - International Workshop on Grounding Language Understanding (D. Jouvet)

GRETSI 2017 - Colloque du Groupe d'Etudes du Traitement du Signal et des Images (R. Serizel)

HSCMA'2017 - Joint Workshop on Hands-free Speech Communication and Microphone Arrays (E. Vincent)

ICASSP'2017 - IEEE International Conference on Acoustics, Speech and Signal Processing (D. Jouvet, A. Liutkus, R. Serizel, E. Vincent)

ICNLSSP'2017 - International Conference on Natural Language, Signal and Speech Processing (D. Jouvet, O. Mella, E. Vincent)

INTERSPEECH 2017 (A. Bonneau, D. Jouvet, I. Illina, Y. Laprie, S. Ouni, E. Vincent)

ISSP 2017 - International Seminar On Speech Production (Y. Laprie)

LVA/ICA'2017 - International Conference on Latent Variable Analysis and Signal Separation (A. Liutkus, E. Vincent)

PaPE 2017 - Phonetics and Phonology in Europe (A. Bonneau)

SLaTE'2017 - ISCA Workshop on Speech and Language Technology in Education (A. Bonneau, D. Jouvet)

WASPAA 2017 - IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (A. Liutkus, R. Serizel, E. Vincent)

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

ANAE Approche Neuropsychologique des Apprentissages chez l'enfant. Coordination of a special issue: N°147 : "Troubles de l'apprentissage du langage écrit et prise en charge multidisciplinaire: De la science à la salle de classe" (A. Piquard-Kipffer)

Computer Speech and Language, special issue on Multi-Microphone Speech Recognition in Everyday Environments (E. Vincent)

EURASIP Journal on Audio, Speech, and Music Processing (Y. Laprie)

Speech Communication (D. Jouvet)

Speech Communication, special issue on Realism in Robust Speech and Language Processing (E. Vincent)

Traitement du signal (E. Vincent)

10.1.3.2. Reviewer - Reviewing Activities

Computer Speech and Language (D. Jouvet)

Computers in Biology and Medicine (R. Serizel)

IEEE Transactions on Audio, Speech and Language Processing (A. Liutkus, S. Ouni, R. Serizel)

IEEE Transactions on Emerging Topics in Computational Intelligence (R. Serizel)

IET Signal Processing (R. Serizel)

Journal of the Acoustical Society of America (B. Elie, Y. Laprie)

Jasa Express Letters (Y. Laprie, S. Ouni, R. Serizel)

Logopedics Phoniatrics Vocology (S. Ouni)

Speech Communication (V. Colotte, S. Ouni)

10.1.4. Invited Talks

Dyslexia-dysorthographia, « Dyslexie-Dysorthographie. Du repérage à la prise en charge ». Unaape, Le Chesnay, Jan 2017 (A. Piquard-Kipffer)

New paradigms in speech recognition, SIIE 2017, Feb 2017 (D. Fohr, I. Illina) [35]

Speech processing techniques for far-end spoken interactions in noisy environments, Sonos, Santa Barbara (US), March 2017 (R. Serizel)

A tutorial on probabilistic modeling for audio source separation, Kyoto University, March 2017 (A. Liutkus)

An articulatory model of the complete vocal tract from medical images, Electronic Speech Signal Processing 2017, Saarbrücken, March 2017 (Y. Laprie)

Language pathology, Séminaire "Dépistage des troubles des apprentissages" in EHESP, Rennes, March 2017 (A. Piquard-Kipffer)

Speech synthesis, Ecole Nationale d'Ingénieurs de Tunis (Tunisia), May 2017 (V. Colotte)

Speech recognition, Ecole Nationale d'Ingénieurs de Tunis (Tunisia), May 2017 (D. Jouvet)

Deep learning for distant-microphone enhancement and recognition — Expected and unexpected results, Audio Analytic, Cambridge (UK), June 2017 (E. Vincent)

Deep learning for speech and audio processing, Journées scientifiques Inria, Sophia-Antipolis, June 2017 (R. Serizel)

Deep learning for distant-microphone enhancement and recognition — Expected and unexpected results, Inria Rennes - Bretagne Atlantique (France), July 2017 (E. Vincent)

When mismatched training data outperform matched data, Erwin Schroedinger Institute Workshop on "Systematic approaches to deep learning methods for audio", Vienna (Austria), Sep 2017 (E. Vincent)

Rehaussement et reconnaissance robuste de la parole, Université Grenoble - Alpes (France), Nov 2017 (E. Vincent)

Reading predictors, "les habiletés associées à la lecture. Comment être le mieux outillé(e) pour apprendre à lire ?". Canopé, Nancy, Nov 2017 (A. Piquard-Kipffer)

Beginning of reading, "Les premiers apprentissages de la lecture". Conférences de circonscriptions 1 et 2. Longwy, Nov 2017 (A. Piquard-Kipffer)

10.1.5. 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)

10.1.6. Scientific Expertise

Expertise of an ANR project proposal (D. Jouvet, Y. Laprie)

Expertise of an ERC project proposal (E. Vincent)

Expertise of the ÖAW - Austrian Academy of Sciences Fund (S. Ouni)

10.1.7. Research Administration

Vice Scientific Deputy of Inria Nancy - Grand Est from Sep 2017 (E. Vincent)

Elected Member of the board of the AM2I Scientific Pole - Université de Lorraine (E. Vincent)

Member of Comité Espace Transfert (E. Vincent)

Member of the Comipers of Inria Nancy - Grand Est until Aug 2017 (E. Vincent)

Member of the Comité de Centre of Inria Nancy - Grand Est until Aug 2017 (E. Vincent)

Vice-Chair of the Recruitment Jury for Junior Research Scientists, Inria Nancy - Grand Est (E. Vincent).

Member of the “Commission de développement technologique” (A. Bonneau)

Head of the AM2I Scientific Pole of Université de Lorraine (Y. Laprie)

Member of the Scientific Committee of an Institute for deaf people, La Malgrange (A. Piquard-Kipffer)

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, Computer science basics, 90 hours, L1, University of Lorraine, France

DUT: R. Serizel, Introduction to office software applications, 18h, L2, University of Lorraine, France

DUT: R. Serizel, Multimedia and web applications, 20h, L1, University of Lorraine, France

DUT: R. Serizel, Digital image processing basics

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, 20h, L1, University of Lorraine, France

Licence: O. Mella, Introduction to Web Programming, 30h, L1, University of Lorraine, France

Licence: O. Mella, Computer Networking, 128h, L2-L3, University of Lorraine, France

Licence: O. Mella Supervision of student internships, 4 hours, L3, University of Lorraine, France

Licence: A. Piquard-Kipffer, Education Science, 32 hours, L1, Departement Orthophonie, University of Lorraine, France

Licence: A. Piquard-Kipffer, Learning to Read, 34 hours, L2, Departement Orthophonie, University of Lorraine, France

Licence: A. Piquard-Kipffer, Psycholinguistics, 12 hours, L2, Departement Orthophonie, University Pierre et Marie Curie-Paris, France

Licence: A. Piquard-Kipffer, Dyslexia, Dysorthographia, 22 hours, L3, Departement Orthophonie, University of Lor- raine, France

Master: A. Bonneau, Ecole d'audioprothèse (Phonetics), 16h, University of Lorraine, France

Master: A. Bonneau, Ecole d'orthophonie (Speech Manipulation with Praat), 2h, University of Lorraine, France

Master: V. Colotte, Introduction to Speech Analysis and Recognition, 18h, M1, University of Lorraine, France

Master: D. Jouvet, Modélisation sensorielle (partie reconnaissance de la parole), 12h, M2, University of Lorraine, France

Master: Y. Laprie, Master de Sciences Cognitives (Analyse, perception et reconnaissance de la parole), 30h, University of Lorraine, France

Master: O. Mella, Computer Networking, 60h, 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 Agnès, Dyslexia, Dysorthographia diagnosis, 4 hours, Departement Orthophonie, University of Lor- raine, France

Master: A. Piquard-Kipffer, Deafness & reading, 21 hours, Departement Orthophonie, University of Lorraine, France

Master: A. Piquard-Kipffer, French Language Didactics, 73 hours, ESPE, University of Lorraine, France

Master: A. Piquard-Kipffer, Special educational needs, 18 hours, ESPE, University of Lorraine, France

Master: A. Piquard-Kipffer, Psychology, 6 hours, University of Lorraine, France

Continuous training : O. Mella, Computer science courses for secondary school teachers (ISN courses), 10h, ESPE, University of Lorraine, France

Doctorat: A. Piquard-Kipffer, Language Pathology, 20 hours, EHESP, University of Sorbonne- Paris Cité, France

Doctorat: A. Piquard-Kipffer, Language Pathology, 20 hours, 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 : Quan Nguyen, "Mapping of a sound environment by a mobile robot", University of Lorraine, November 3, 2017, Francis Colas and Emmanuel Vincent.

PhD : Aditya Nugraha, "Deep neural networks for source separation and noise-robust speech recognition", December 5, 2017, 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 (Ircam).

PhD in progress: Amal Houidhek, “Élaboration et analyse d’une base de parole arabe pour la synthèse vocale”, December 2015, cotutelle, 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, codirection, Denis Jouvet and Vincent Colotte (France) and Zied Mnasri (Tunisia).

PhD in progress: Amine Menacer, “Traduction automatique de vidéos”, May 2016, Kamel Smaïli and Denis Jouvet.

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: 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 (IRISA) and Emmanuel Vincent.

PhD in progress: Lauréline Perotin, “Séparation aveugle de sources sonores en milieu réverbérant”, November 2016, Romain Serizel, Emmanuel Vincent, and Alexandre Guérin (Orange).

PhD in progress: Théo Biasutto, “Multimodal coarticulation modeling: Towards the animation of an intelligible speaking head”, December 2016, Slim Ouni.

PhD in progress: Sara Dahmani, “Modeling facial expressions to animate a realistic 3D virtual talking head”, January 2017, Slim Ouni and Vincent Colotte.

PhD in progress: Guillaume Carbajal, “Apprentissage profond bout-en-bout pour le rehaussement de la parole”, March 2017, Romain Serizel, Emmanuel Vincent, and AÉric Humbert (Invoxia).

PhD in progress: Sunit Sivasankaran, “Exploiting contextual information in the speech processing chain”, July 2017, Dominique Fohr and Emmanuel Vincent.

PhD in progress: Ioannis Douros, “Combining cineMRI and static MRI to analyze speech production”, July 2017, Pierre-André Vuissoz (IADI) and Yves Laprie.

PhD in progress: Lou Lee, “Du lexique au discours: les particules discursives en français”, October 2017, Yvon Keromnes and Mathilde Dargnat (ATILF) and Denis Jouvet.

10.2.3. Participation in HDR and PhD juries

Participation in Habilitation Jury for Damien Lolive (Université de Rennes 1, November 2017), Y. Laprie, reviewer.

Participation in PhD thesis Jury for Dionyssos Kounades-Bastian (Université Grenoble - Alpes, February 2017), E. Vincent, reviewer.

Participation in PhD thesis Jury for Emilio Molina Martínez (University of Málaga, Spain, March 2017), E. Vincent, reviewer.

Participation in PhD thesis Jury for Simon Durand (Télécom ParisTech, May 2017), E. Vincent, reviewer.

Participation in PhD thesis Jury for Mathieu Baqué (Université du Maine, June 2017), E. Vincent, reviewer.

Participation in PhD thesis Jury for Waad Ben Kheder (Université d’Avignon et des Pays du Vaucluse, July 2017), R. Serizel.

Participation in PhD thesis Jury for Waad Ben Kheder (Université d’Avignon et des Pays du Vaucluse, July 2017), D. Jouvet, reviewer.

Participation in PhD thesis Jury for Gabriel Bustamante (Université Fédérale Toulouse Midi-Pyrénées, September 2017), E. Vincent, reviewer.

Participation in PhD thesis Jury for Fangchen Feng (Université Paris - Sud, September 2017), E. Vincent, reviewer.

Participation in PhD thesis Jury for Gregory Gelly (Université Paris-Saclay, September 2017), D. Jouvet, reviewer.

Participation in PhD thesis Jury for Andrew Szabados (Université de Grenoble Alpes, November 2017), Y. Laprie, reviewer.

Participation in PhD thesis Jury for Natalia Tomashenko (Université du Mans, December 2017), D. Jouvet, reviewer.

Participation in PhD thesis Jury for Daniele Battaglino (EURECOM - Télécom ParisTech, December 2017), E. Vincent, reviewer.

Participation in PhD thesis Jury for Mohamed Bouaziz (Université d'Avignon, December 2017), I. Illina, reviewer.

Participation in PhD thesis Jury for Inaki Frenandez (Université de lorraine, December 2017), I. Illina.

10.2.4. Participation in other juries

Participation in CAFIPEMPF Jury - Master Learning Facilitator, Académie de Nancy-Metz & Université de Lorraine, April, May 2017, A. Piquard-Kipffer

Participation in the Competitive Entrance Examination into Speech-Language Pathology Departement, Université de Lorraine, June 2017, A. Piquard-Kipffer.

10.3. Popularization

Interview for “Quand les machines apprennent à parler l'humain — Le Zoom de la Rédaction”, *France Inter*, February 2, 2017 (E. Vincent)

Interview for “Les prochains défis de la reconnaissance vocale”, *Le Figaro*, April 11, 2017 (E. Vincent)

Interview for “2017 : Alexa, la voix d'Amazon”, *Les Échos*, August 31, 2017 (E. Vincent)

Interactions vocales, Grand-Est Numérique, September 2017 (R. Serizel)

Demonstrations at Fête de la Science, University of Lorraine, October 13, 2017 (G. Carbajal, L. Perotin, R. Serizel, E. Vincent)

Demonstrations at the Rencontre Inria Industrie “Les données et leurs applications”, October 18, 2017 (E. Vincent)

Interview for “Les assistants vocaux vont bousculer la radio”, *Le Monde*, October 19, 2017 (E. Vincent)

Interview for *France Culture*, November 2017 (E. Vincent)

Talk at “Fresh from the Labs”, Station F, Paris (France), November 30, 2017 (E. Vincent)

Demonstration at Journée des métiers, Collège Péguy, le Chesnay, March 2017 (A. Piquard-Kipffer).

Demonstration of Dynalips at “50 ans Inria”, Paris, November, 7-8, 2017 (S. Ouni)

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, B. CHRISTIAN.*Je peux voir les mots que tu dis ! Histoire d'un projet*, in "13ème édition du Festival du film de chercheur CNRS 2012", Nancy, France, June 2012, https://hal.inria.fr/hal-01263907.

[8] 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

Articles in International Peer-Reviewed Journal

[9] J. BARKER, R. MARXER, E. VINCENT, S. WATANABE.*Multi-microphone speech recognition in everyday environments*, in "Computer Speech and Language", July 2017, vol. 46, p. 386-387 [*DOI :* 10.1016/J.CSL.2017.02.007], https://hal.inria.fr/hal-01483469.

[10] J. BARKER, R. MARXER, E. VINCENT, S. WATANABE.*The third 'CHIME' speech separation and recognition challenge: Analysis and outcomes*, in "Computer Speech and Language", July 2017, vol. 46, p. 605-626, https://hal.inria.fr/hal-01382108.

[11] V. BISOT, R. SERIZEL, S. ESSID, G. RICHARD.*Feature Learning with Matrix Factorization Applied to Acoustic Scene Classification*, in "IEEE/ACM Transactions on Audio, Speech and Language Processing", May 2017, vol. 25, n^{o} 6, p. 1216 - 1229, https://hal.archives-ouvertes.fr/hal-01362864.

[12] B. ELIE, Y. LAPRIE.*Acoustic impact of the gradual glottal abduction on the production of fricatives: A numerical study*, in "Journal of the Acoustical Society of America", September 2017, vol. 142, n^{o} 3, p. 1303-1317 [*DOI :* 10.1121/1.5000232], https://hal.archives-ouvertes.fr/hal-01423206.

[13] B. ELIE, Y. LAPRIE.*Simulating alveolar trills using a two-mass model of the tongue tip*, in "Journal of the Acoustical Society of America", 2017, vol. 142, n^{o} 5, https://hal.archives-ouvertes.fr/hal-01525882.

[14] 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", April 2017, vol. 25, n^{o} 4, p. 692–730, Added equation (108), https://hal.inria.fr/hal-01414179.

[15] C. Leclerc, A. Piquard-Kipffer, C. Rosin, M. Wernet.*Inclusive education: a particular system of teaching with dyslexic and dysphasicchildren, in a specialized school*, in "ANAE - Approche Neuropsychologique des Apprentissages Chez L'enfant", October 2017, https://hal.inria.fr/hal-01635918.

[16] T. Léonova, A. Piquard-Kipffer, A. Jumageldinov, M. Robert, M. Berebin.*Inclusive education for students with specific language disorders: What schoolingaccording to country and language*, in "ANAE - Approche Neuropsychologique des Apprentissages Chez L'enfant", October 2017, https://hal.inria.fr/hal-01647486.

[17] K. Nathwani, E. Vincent, I. Illina.*DNN Uncertainty Propagation using GMM-Derived Uncertainty Features for Noise Robust ASR*, in "IEEE Signal Processing Letters", January 2018, https://hal.inria.fr/hal-01680658.

[18] A. Piquard-Kipffer, T. Léonova.*Scolarité et handicap : parcours de 170 jeunes dysphasiques ou dyslexiques- dysorthographiques âgés de 6 à 20 ans*, in "ANAE - Approche Neuropsychologique des Apprentissages Chez L'enfant", October 2017, https://hal.inria.fr/hal-01645096.

[19] 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.

[20] I. A. Sheikh, D. Fohr, I. Illina, G. Linares.*Modelling Semantic Context of OOV Words in Large Vocabulary Continuous Speech Recognition*, in "IEEE/ACM Transactions on Audio, Speech and Language Processing", January 2017, vol. 25, n^{o} 3, p. 598 - 610 [*DOI :* 10.1109/TASLP.2017.2651361], https://hal.inria.fr/hal-01461617.

[21] S. Sivasankaran, E. Vincent, I. Illina.*A combined evaluation of established and new approaches for speech recognition in varied reverberation conditions*, in "Computer Speech and Language", July 2017, vol. 46, p. 444-460, https://hal.inria.fr/hal-01461382.

[22] 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", July 2017, vol. 46, p. 535-557, https://hal.inria.fr/hal-01399180.

[23] Z. Wang, E. Vincent, R. Serizel, Y. Yan.*Rank-1 Constrained Multichannel Wiener Filter for Speech Recognition in Noisy Environments*, in "Computer Speech and Language", 2017, https://hal.inria.fr/hal-01634449.

Invited Conferences

[24] A. Mesaros, T. Heittola, A. Diment, B. Elizalde, A. Shah, E. Vincent, B. Raj, T. Virtanen.*DCASE 2017 Challenge setup: Tasks, datasets and baseline system*, in "DCASE 2017 - Workshop on Detection and Classification of Acoustic Scenes and Events", Munich, Germany, November 2017, https://hal.inria.fr/hal-01627981.

[25] E. VINCENT.*When mismatched training data outperform matched data*, in "Systematic approaches to deep learning methods for audio", Vienna, Austria, September 2017, https://hal.inria.fr/hal-01588876.

International Conferences with Proceedings

[26] I. BADA, J. KARSTEN, D. FOHR, I. ILLINA.*Data Selection in the Framework of Automatic Speech Recognition*, in "ICNLSSP 2017 - International conference on natural language, signal and speech processing 2017", Casablanca, Morocco, Proceedings of ICNLSSP 2017, December 2017, p. 1-5, https://hal.archives-ouvertes.fr/hal-01629340.

[27] V. BISOT, R. SERIZEL, S. ESSID, G. RICHARD.*Leveraging deep neural networks with nonnegative representations for improved environmental sound classification*, in "IEEE International Workshop on Machine Learning for Signal Processing MLSP", Tokyo, Japan, September 2017, https://hal.archives-ouvertes.fr/hal-01576857.

[28] V. BISOT, R. SERIZEL, S. ESSID, G. RICHARD.*Nonnegative Feature Learning Methods for Acoustic Scene Classification*, in "DCASE 2017 - Workshop on Detection and Classification of Acoustic Scenes and Events", Munich, Germany, November 2017, https://hal.inria.fr/hal-01636627.

[29] B. DENG, D. JOUVET, Y. LAPRIE, I. STEINER, A. SINI.*Towards Confidence Measures on Fundamental Frequency Estimations*, in "IEEE International Conference on Acoustics, Speech and Signal Processing", New Orleans, United States, March 2017, https://hal.inria.fr/hal-01493168.

[30] D. DI CARLO, K. DÉGUERNEL, A. LIUTKUS.*Gaussian framework for interference reduction in live recordings*, in "AES International Conference on Semantic Audio", Erlangen, Germany, June 2017, https://hal.inria.fr/hal-01515971.

[31] B. DUMORTIER, E. VINCENT, M. DEACONU.*Recursive Bayesian estimation of the acoustic noise emitted by wind farms*, in "2017 IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)", New Orleans, United States, March 2017, https://hal.inria.fr/hal-01428962.

[32] K. DÉGUERNEL, J. NIKA, E. VINCENT, G. ASSAYAG.*Generating Equivalent Chord Progressions to Enrich Guided Improvisation : Application to Rhythm Changes*, in "SMC 2017 - 14th Sound and Music Computing Conference", Espoo, Finland, July 2017, 8, https://hal.inria.fr/hal-01528559.

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[35] D. FOHR, O. MELLA, I. ILLINA.*New Paradigm in Speech Recognition: Deep Neural Networks*, in "IEEE International Conference on Information Systems and Economic Intelligence", Marrakech, Morocco, April 2017, https://hal.archives-ouvertes.fr/hal-01484447.

[36] M. FONTAINE, A. LIUTKUS, L. GIRIN, R. BADEAU.*Explaining the Parameterized Wiener Filter with Alpha-Stable Processes*, in "IEEE Workshop on Applications of Signal Processing to Audio and Acoustics

(WASPAA)", New Paltz, New York, United States, Proc. IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA), October 2017, https://hal.archives-ouvertes.fr/hal-01548508.

[37] M. FONTAINE, C. VANWYNSBERGHE, A. LIUTKUS, R. BADEAU.*Scalable Source Localization with Multichannel Alpha-Stable Distributions*, in "25th European Signal Processing Conference (EUSIPCO)", Kos, Greece, Proc. of 25th European Signal Processing Conference (EUSIPCO), August 2017, p. 11-15, https://hal.archives-ouvertes.fr/hal-01531252.

[38] 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, Latent Variable Analysis and Signal Separation 13th International Conference, LVA/ICA 2017, Grenoble, France, February 21-23, 2017, Proceedings, February 2017, vol. 10169, p. 80-88 [*DOI :* 10.1007/978-3-319-53547-0_8], https://hal.archives-ouvertes.fr/hal-01401988.

[39] *Best Paper*
A. HOUIDHEK, V. COLOTTE, Z. MNASRI, D. JOUVET, I. ZANGAR.*Statistical modelling of speech units in HMM-based speech synthesis for Arabic*, in "LTC 2017 - 8th Language & Technology Conference", Poznań, Poland, November 2017, p. 1-5, https://hal.inria.fr/hal-01649034.

[40] I. ILLINA, D. FOHR.*Out-of-Vocabulary Word Probability Estimation using RNN Language Model*, in "8th Language & Technology Conference", Poznan, Poland, proceedings of LTC 2017, November 2017, https://hal.archives-ouvertes.fr/hal-01623784.

[41] D. JOUVET, K. BARTKOVA, M. DARGNAT, L. LEE.*Analysis and Automatic Classification of Some Discourse Particles on a Large Set of French Spoken Corpora*, in "SLSP'2017, 5th International Conference on Statistical Language and Speech Processing", Le Mans, France, October 2017, https://hal.inria.fr/hal-01585567.

[42] *Best Paper*
D. JOUVET, D. LANGLOIS, M. A. MENACER, D. FOHR, O. MELLA, K. SMAÏLI.*About vocabulary adaptation for automatic speech recognition of video data*, in "ICNLSSP'2017 - International Conference on Natural Language, Signal and Speech Processing", Casablanca, Morocco, December 2017, p. 1-5, https://hal.inria.fr/hal-01649057.

[43] D. JOUVET, Y. LAPRIE.*Performance Analysis of Several Pitch Detection Algorithms on Simulated and Real Noisy Speech Data*, in "EUSIPCO'2017, 25th European Signal Processing Conference", Kos, Greece, August 2017, https://hal.inria.fr/hal-01585554.

[44] Y. LAPRIE, B. ELIE, P.-A. VUISSOZ, A. TSUKANOVA.*Articulatory model of the epiglottis*, in "The 11th International Seminar on Speech Production", Tianjin, China, October 2017, https://hal.inria.fr/hal-01643227.

[45] 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.

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[47] A. LIUTKUS, K. YOSHII.*A diagonal plus low-rank covariance model for computationally efficient source separation*, in "IEEE international workshop on machine learning for signal processing (MLSP)", Tokyo, Japan, September 2017, https://hal.inria.fr/hal-01580733.

[48] P. MAGRON, R. BADEAU, A. LIUTKUS.*Lévy NMF : un modèle robuste de séparation de sources non-négatives*, in "Colloque GRETSI", Juan-Les-Pins, France, Actes du XXVIème Colloque GRETSI, September 2017, https://hal.archives-ouvertes.fr/hal-01540484.

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[52] M. A. MENACER, O. MELLA, D. FOHR, D. JOUVET, D. LANGLOIS, K. SMAÏLI.*Development of the Arabic Loria Automatic Speech Recognition system (ALASR) and its evaluation for Algerian dialect*, in "ACLing 2017 - 3rd International Conference on Arabic Computational Linguistics", Dubai, United Arab Emirates, November 2017, p. 1-8, https://hal.archives-ouvertes.fr/hal-01583842.

[53] K. NATHWANI, J. A. MORALES-CORDOVILLA, S. SIVASANKARAN, I. ILLINA, E. VINCENT.*An extended experimental investigation of DNN uncertainty propagation for noise robust ASR*, in "5th Joint Workshop on Hands-free Speech Communication and Microphone Arrays (HSCMA 2017)", San Francisco, United States, March 2017, https://hal.inria.fr/hal-01446441.

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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 Medicine

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:

A3.3. - Data and knowledge analysis
A3.4. - Machine learning and statistics
A5.1.3. - Haptic interfaces
A5.1.4. - Brain-computer interfaces, physiological computing
A5.9.2. - Estimation, modeling
A5.11.1. - Human activity analysis and recognition
A6.1.1. - Continuous Modeling (PDE, ODE)
A6.1.2. - Stochastic Modeling (SPDE, SDE)
A6.1.4. - Multiscale modeling
A6.2.1. - Numerical analysis of PDE and ODE
A6.3.4. - Model reduction
A9.2. - Machine learning
A9.3. - Signal analysis

Other Research Topics and Application Domains:

B1.2. - Neuroscience and cognitive science
B1.2.1. - Understanding and simulation of the brain and the nervous system
B1.2.2. - Cognitive science
B2.2.2. - Nervous system and endocrinology
B2.5.1. - Sensorimotor disabilities
B2.6.1. - Brain imaging
B2.8. - Sports, performance, motor skills

1. Personnel

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Christelle Lévèque [university of Lorraine]

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 anesthesia.

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.

After extracting models for different description levels, they are typically 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 requires contact with 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 behavior 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 anesthesia 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 general anesthesia: loss of consciousness, immobility, amnesia and analgesia.

During general anesthesia, the electroencephalogram (EEG) on the scalp changes characteristically: increasing the anesthetic 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 anesthetist in the control of the anesthesia depths of patients during surgery. However, the conventional monitors exhibit a large variability between the detected anesthetic 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 anesthesia 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 anesthesia and a weak EEG-online monitoring system during anesthesia. Consequently, to improve the situation of patients during and after surgery and to develop improved anesthetic 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 anesthesia, it is necessary to study neural population dynamics subject to the concentration of anesthetic 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, modeling 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 anesthetic 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 anesthesia. More specifically, for deeper anesthesia, 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 anesthesia. 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 anesthesia was only partial, declarative memory being maintained in some unexplained cases. It is still unknown how memory can be maintained under general anesthesia and it needs to be investigated to improve the recovery from anesthesia and to avoid as much as possible post-traumatic disorders. To learn more about memory under anesthesia, 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 anesthesia 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 improve 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 is one of the three members of the committee, with Laurent Koessler and Stéphanie Caharel, that has successfully valued and amplified Neuroscience in Lorraine building a network of research in neuroscience at university of Lorraine. Neuroscience is currently being developed in different laboratories at the university of Lorraine in different institutes such as Inria, CNRS, INSERM, INRA and the university hospital of Nancy. The network will bring together more than 80 researchers in neuroscience to propose common researchers and to give national and international visibilities to neuroscience in Lorraine.
- Neurosys is the leader of the Brain-Computer Interface (BCI) for stroke platform in the Inria Project Lab BCI LIFT (see section 8.2). We developed Grasp'it, an innovative Brain-Computer Interface designed to enhance the motor rehabilitation of stroke patients with Stéphanie Fleck from Perseus lab at university of Lorraine [7], [11], [14]. Our system records users' cerebral activity during the kinesthetic motor imageries (KMI) execution using an electroencephalographic system and gives patients some visual feedback according to the accuracy of the performed imagined task. The graspIT platform was ranked second in the IHM2017 conference demonstrations and first in terms of utility. Grasp'it tends to become a serious game, whose aim is to support the learning and the practice of the KMI tasks in playful and motivating conditions. A French national (ANR) project has been submitted with two other Inria teams (Hybrid and Camin), three rehabilitation centers and an industrial partner, OpenEdge.

6. New Software and Platforms

6.1. 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

6.2. OpenVIBE

KEYWORDS: Neurosciences - Interaction - Virtual reality - Health - Real time - Neurofeedback - Brain-Computer Interface - EEG - 3D interaction

FUNCTIONAL DESCRIPTION: OpenViBE is a free and open-source software platform devoted to the design, test and use of Brain-Computer Interfaces (BCI). The platform consists of a set of software modules that can be integrated easily and efficiently to design BCI applications. The key features of OpenViBE software are its modularity, its high-performance, its portability, its multiple-users facilities and its connection with high-end/VR displays. The designer of the platform enables to build complete scenarios based on existing software modules using a dedicated graphical language and a simple Graphical User Interface (GUI). This software is available on the Inria Forge under the terms of the AGPL licence, and it was officially released in June 2009. Since then, the OpenViBE software has already been downloaded more than 40000 times, and it is used by numerous laboratories, projects, or individuals worldwide. More information, downloads, tutorials, videos, documentations are available on the OpenViBE website.

- Participants: Cédric Riou, Thierry Gaugry, Anatole Lécuyer, Fabien Lotte, Jussi Tapio Lindgren, Laurent Bougrain, Maureen Clerc Gallagher and Théodore Papadopoulo
- Partners: INSERM - CEA-List - GIPSA-Lab
- Contact: Anatole Lécuyer
- URL: http://openvibe.inria.fr

6.3. Platforms

6.3.1. EEG experimental room

A room at Inria Nancy - Grand Est is 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). Our Biosemi EEG amplifier has been extended this year to record 128 channels (Regional initiative *Contrat de Projet État Région (CPER) IT2MP* see section 8.1).

7. New Results

7.1. From the microscopic to the mesoscopic scale

Participants: Laure Buhry, Axel Hutt, Francesco Giovannini, Mélanie Aussel, Ivan Kotiuchi.

In collaboration with Radu Ranta (university of Lorraine), Beate Knauer and Motoharu Yoshida (Ruhr university) and LieJune Shiau (university of Houston)

Figure 1. Electroencephalographic Experimental room at Inria Nancy-Grand Est

7.1.1. Memory and anesthesia

7.1.1.1. Modeling effects of propofol anesthesia

Neural oscillations are thought to be correlated with the execution of cognitive functions. Indeed, gamma oscillations are often recorded in functionally-coupled brain regions for cooperation during memory tasks, and this rhythmic behavior is thought to result from synaptic GABAergic interactions between interneurons. Interestingly, GABAergic synaptic and extrasynaptic receptors have been shown to be the preferred target of the most commonly used anesthetic agents. We presented a in-depth computational study [0] [1] of the action of anesthesia on neural oscillations by introducing a new mathematical model which takes into account the four main effects of the anesthetic agent propofol on GABAergic hippocampal interneurons. These are: the action on synaptic $GABA_A$ receptors, which includes an amplification and an extension of the duration of the synaptic currents, as well as an increase in current baseline, and the action on extrasynaptic $GABA_A$ receptors mediating a tonic inhibitory current. Our results indicate that propofol-mediated tonic inhibition contributes to an unexpected enhancement of synchronization in the activity of a network of hippocampal interneurons. This enhanced synchronization could provide a possible mechanism supporting the occurrence of intraoperative awareness, explicit memory formation, and even paradoxical excitation under general anesthesia, by transiently facilitating the communication between brain structures which should supposedly be not allowed to do so when anesthetized.

7.1.1.2. Stability Analysis in a model of hippocampal place cells

Ring networks, a particular form of Hopfield neural networks, can be used to model the activity of place cells, a type of cells in the hippocampus that are involved in the building and memorization of a cognitive map of one's environment. The behavior of these models is highly dependent on their recurrent synaptic connectivity matrix and on individual neurons' activation function, which must be chosen appropriately to obtain physiologically meaningful conclusions. In [4], we proposed several simpler ways to adjust this synaptic connectivity matrix compared to existing literature so as to achieve stability in a ring attractor network with a piece-wise affine activation functions, and we link these results to the possible stable states the network can converge to.

7.1.1.3. Modeling of the hippocampal formation over the sleep-wake cycle :

The hippocampus can exhibit different oscillatory rhythms within the sleep-wake cycle, each of them being involved in cognitive processes. For example, theta-nested gamma oscillations, consisting of the coupling of theta (4-12Hz) and gamma (40-100Hz) rhythms, are produced during wakefulness and are associated with spatial navigation tasks, whereas Sharp-Wave-Ripple (SWR) complexes, consisting of fast (140-200Hz)

[0] F. Giovannini and L. Buhry, Tonic inhibition mediates a synchronization enhancement during propofol anesthesia in a network of hippocampal interneurons: a modeling study Journal of computational neuroscience (Submitted) 2017

oscillatory events occurring at low ($\leq$ 0.5Hz) frequencies, are produced during slow-wave sleep and play an important role in memory consolidation. The mechanisms underlying the generation and switch between each of these rhythms is not yet fully understood, but Acetylcholine is thought to play a key role in it.

In an article in preparation, we propose a computational model of the hippocampal formation based on a realistic topology and synaptic connectivity, influenced by the changing concentration of Acetylcholine between wakefulness and sleep. By using a detailed estimation of intracerebral recordings, we show that this model is able to reproduce both the theta-nested gamma oscillations that are seen in awake brains and the sharp-wave ripple complexes that appear during slow-wave sleep. The results of our simulations support the idea that the functional connectivity of the hippocampus is a key factor in controlling its rhythms.

7.2. From the Mesoscopic to the Macroscopic Scale

Participants: Laurent Bougrain, Axel Hutt, Tamara Tošić, Cecilia Lindig-León, Romain Orhand, Sébastien Rimbert, Oleksii Avilov, Rahaf Al-Chwa.
In collaboration with Stéphanie Fleck (Univ. Lorraine)

7.2.1. Motor system

In collaboration with Stéphanie Fleck (Univ. Lorraine)
Kinesthetic motor imagery (KMI) tasks induce brain oscillations over specific regions of the primary motor cortex within the contralateral hemisphere of the body part involved in the process. This activity can be measured through the analysis of electroencephalographic (EEG) recordings and is particularly interesting for Brain-Computer Interface (BCI) applications.

7.2.1.1. Continuous and discrete

In most BCI experimental paradigms based on Motor Imagery (MI), subjects perform continuous motor imagery (CMI), i.e., a repetitive and prolonged intention of movement, for a few seconds. To improve efficiency such as detecting faster a motor imagery and thus avoid fatigue and boredom, we proposed to show the difference between discrete motor imagery (DMI), i.e., a single short MI, and CMI. The results of the experiment involving 13 healthy subjects suggest that DMI generates a robust post-MI event-related synchronization (ERS). Moreover event-related desynchronization (ERD) produced by DMI seems less variable in certain cases compared to CMI [10], [12]. We showed the difference, in term of classification, between a DMI and a CMI. The results of the experiment involving 16 healthy subjects show that a BCI based on DMI is as effective as a BCI based on CMI and could be used to allow a faster detection [6].

7.2.1.2. Profiling

The most common approach for classification consists of analyzing the signal during the course of the motor task within a frequency range including the alpha band, which attempts to detect the Event-Related Desynchronization (ERD) characteristics of the physiological phenomenon. However, to discriminate right-hand KMI and left-hand KMI, this scheme can lead to poor results on subjects for which the lateralization is not significant enough. To solve this problem, we proposed to analyze the signal at the end of the motor imagery within a higher frequency range, which contains the Event-Related Synchronization (ERS). We showed that 6 out of 15 subjects have a higher classification rate after the KMI than during the KMI, due to a higher lateralization during this period. Thus, for this population we obtained a significant improvement of 13% in classification taking into account the users lateralization profile [9].

7.2.1.3. Combined motor imageries

Combined motor imageries can be detected to deliver more commands in a Brain-Computer Interface for controlling a robotic arm. Nevertheless only a few systems use more than three motor imageries: right hand, left hand and feet. Combining them allows to get four additional commands. We presented an electrophysiological study to show that i) simple motor imageries have mainly an electrical modulation over the cortical area related the body part involved in the imagined movement and that ii) combined motor imageries reflect a superposition of the electrical activity of simple motor imageries. A shrinkage linear discriminant analysis has been used to test as a first step how a resting state and seven motor imageries can be detected. 11 healthy subjects participated in the experiment for which an intuitive assignment has been done to associate motor imageries and movements of the robotic arm with 7 degrees of freedom [2], [5].

7.2.1.4. *Anesthesia*

Each year, several million of general anesthesia are realized in France. A recent study shows that, between 0.1-0.2 % of patients are victims of intraoperative awareness. This kind of awakening could cause post-traumatic syndromes for the patient. Unfortunately, today, no monitoring system is able to avoid the intraoperative awareness phenomenon. Interestingly, if there is no subject movement due to curare, an electroencephalographical study of the motor cortex can help to detect an intention of movement. The dynamic study of motor cerebral activity during general anesthesia is essential if we want to create a brain-computer interface adapted to the detection of intraoperative awareness. We wrote a clinical protocol to allow EEG data recording during general anesthesia with propofol. Then, the development of temporal analysis specific methods allows us to quantify patterns of desynchronization and synchronization phases observed in delta, alpha and beta frequency bands to prevent intraoperative awareness [8].

8. Partnerships and Cooperations

8.1. Regional Initiatives

Within 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*) observing electroencephalographic activity of humans during motor tasks. Contact in Neurosys is Laurent Bougrain.

8.2. National Initiatives

Inria project-Lab BCI-LIFT, Brain-Computer Interfaces: Learning, Interaction, Feedback, Training, Maureen Clerc, 2015-2018, 7 Inria project-teams (Aramis, Athena, Demar, Hybrid, Mjolnir, Neurosys, Potioc), university of Rouen, Dycog team at Centre de Recherche en Neurosciences de Lyon.

BCI-LIFT is a research initiative to reach a next generation of non-invasive Brain-Computer Interfaces (BCI), more specifically BCI that are easier to appropriate, more efficient, and suit a larger number of people. With this concern of usability as our driving objective, we build non-invasive systems that benefit from advanced signal processing and machine learning methods, from smart interface design, and where the user immediately receives supportive feedback. What drives this project is the concern that a substantial proportion of human participants is currently categorized “BCI-illiterate” because of their apparent inability to communicate through BCI. Through this project we aim at making it easier for people to learn to use BCI, by implementing appropriate machine learning methods and developing user training scenarios.

8.3. International Initiatives

8.3.1. Inria International Partners

8.3.1.1. *Informal International Partners*

- We have an ongoing collaboration with Prof. Motoharu Yoshida at 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).
- We also collaborate with Anton Popov (Kiev Polytechnic Institute, Ukraine) on feature extraction of brain signal and deep learning (L. Bougrain).

8.4. International Research Visitors

8.4.1. Visits of International Scientists

- Anton Popov, Ass. Prof, Kiev Polytechnic Institute, Ukraine, 5 weeks (May 2017)
- Yevgeniy Karplyuk, Ass. Prof, Kiev Polytechnic Institute, Ukraine, 3 weeks (May 2017)
- Widodo Budiharto, Full Prof, university of Binus, Indonesia, 1 week (Jan 2017)

8.4.1.1. Internships

- Oleksii Avilov, Erasmus+, Kiev Polytechnic Institute, Ukraine, Jan-Jul 2017
- Ivan Kotiuchi, Erasmus+, Kiev Polytechnic Institute, Ukraine, Jan-Jul 2017

9. Dissemination

9.1. Promoting Scientific Activities

Laurent Bougrain is a member of the steering committee of the research network in neuroscience of the university of Lorraine.

Laure Buhry is an elected member of the "Pôle Scientifique AM2I" council of university of Lorraine.

Sébastien Rimbert is an elected member of the doctoral school IAEM of university of Lorraine.

9.1.1. Scientific Events Organisation

9.1.1.1. Member of the Organizing Committees

- Member of the organization committee of the launch day of the French society of brain-computer interfaces, January 24th 2017, Paris (L. Bougrain) http://openvibe.inria.fr/the-2nd-international-openvibe-workshop-2016-contents/
- Member of the organization committee of the iPAC seminar (Image, Perception, Action et Cognition) (L. Buhry)
- Member of the organization committee of the scientific days of the research network in neuroscience of the university of Lorraine, June 9th & November 9th 2017, Nancy (L. Bougrain)

9.1.2. Journal

9.1.2.1. Reviewer - Reviewing Activities

PeerJ (S. Rimbert)

9.1.3. Research Administration

Juries for the recruitment of assistant professors: job MCF4289 IUT university of Cergy Pontoise (2017), L.Buhry

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Engineering school: L. Bougrain, *Interfaces cerveau-ordinateur*, 4.5h, 3rd year, Supelec, France
Polytechnical university of Kiev: L. Bougrain, *Brain-Computer Interfaces*, 10h, master, Ukraine
Engineering School: F. Giovannini, *Artificial Intelligence*, 32h, 3rd year, Telecom Nancy, France
UFR Math/Info: S. Rimbert, *Brain-Computer Interface*, 17h, Master 2, UFR Math/Info, France
UFR Math/Info: S. Rimbert, *Introduction to Neurosciences*, 15h, 1st year, UFR Math/Info, France
UFR Math/Info: A. Aussel, *Computational Neurosciences*, 20h, Master 2, UFR Math/Info, France
Engineering school: A. Aussel, *Python Programming*, 40h, 1st year, Mines Nancy, France

9.2.2. Supervision

PhD: Francesco Giovannini, Mathematical modelling of neural oscillations in hippocampal memory networks during waking and under general anaesthesia, university of Lorraine, September 19th 2017, Laure Buhry and Axel Hutt [1]

PhD: Cecilia Lindig-León, Multilabel classification of EEG-based combined motor imageries implemented for the 3D control of a robotic arm, January 10th 2017, A. Hutt and L. Bougrain [2]

PhD in progress: Amélie Aussel, Extraction of electrophysiological markers and mathematical modelling of the epileptic hippocampus, October 1st 2016, Laure Buhry and Radu Ranta (CRAN)

PhD in progress: Sébastien Rimbert, Study of the dynamic of cerebral motor patterns during general anesthesia, January 1st 2016, Axel Hutt and Laurent Bougrain

9.2.3. Juries

Ph.D. thesis juries: Loïc Botrel, Brain-computer interfaces (BCIs) based on sensorimotor rhythms Evaluating practical interventions to improve their performance and reduce BCI inefficiency, university of Würzburg, September 27th 2017, L. Bougrain (member)

Ph.D. thesis juries: Marie-Caroline Schaeffer, Traitement du signal ECoG pour Interface Cerveau Machine à grand nombre de degrés de liberté pour application clinique, university Grenoble-Alpes, June 6th 2017, L. Bougrain (member)

9.3. Popularization

Talk during the National Brain Awareness Week: Brain-Robot interactions, Mar. 14th, 2017, middle school Ernest Bichat, Lunéville (L. Bougrain)

Expert for the MGEN (a French mutual benefit insurance company)'s day about "réparer les vivants", Mar. 15th, 2017, Maisons-Alfort (L. Bougrain)

Scientific education on Information Technologgy with Marie Duflot-Kremer in the Marcel Leroy elementary school (20-22 students per class: CM2, CE2 / CM1, CE1 / CE2), 3h (three times 1h), May 30th 2017 (Tamara Tošić)

Exhibit of the Grasp-IT system to improve motor activity at the Interactions Homme-Machine conference 2017, August 2017, Poitier (Sébastien Rimbert)

Exhibit of the Grasp-IT system to improve motor activity at Inria-Industry Meeting on data and their applications, October 18th 2017, Paris (L. Bougrain & Sébastien Rimbert)

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Publications of the year

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[2] C. LINDIG LEÓN.*Multilabel classification of EEG-based combined motor imageries implemented for the 3D control of a robotic arm*, Université de Lorraine, January 2017, https://tel.archives-ouvertes.fr/tel-01549139.

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.

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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

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Project-Team ORPAILLEUR

Creation of the Project-Team: 2008 January 01

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1. Personnel

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Chedy Raïssi [Inria, Researcher]
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Martine Kuhlmann [CNRS]

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. In this view, KDD is an exploratory process similar to “exploratory data analysis”.

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* (KDDK). In KDDK, 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, data exploration, formal concept analysis, classification, pattern mining, numerical methods in data mining.

Knowledge discovery in databases (KDD) aims 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 [78]) and extensions of FCA such as Pattern Structures [84] 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. Other numerical methods in data mining which are also of interest for the team are Random Forests, SVM, and neural networks.

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 exploratory process “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 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 [78] (concept lattices are also known as "Galois lattices" [71]).

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 [91].

3.2. Text Mining

Keywords: text mining, knowledge discovery from texts, text classification, annotation, ontology engineering from texts.

The objective of a text mining process is to extract useful knowledge units from large collections of texts [67]. 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 difficult task. 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 aims at extracting "interesting units" (nouns and relations) from texts with the help of domain knowledge encoded within a knowledge base. The process is roughly similar for text annotation. Text mining is especially useful in the context of semantic web for ontology engineering. In the Orpailleur team, we work 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. Following 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 knowledge bases (domain ontologies) are of main importance. OWL is the knowledge representation language used to design ontologies and knowledge bases, which is based on description logics (DLs [68]). In OWL, knowledge units are represented by classes (DL concepts) having properties (DL roles) and instances. Concepts can be organized within a partial order based on a subsumption relation, and the inference services are based on satisfiability, 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 [69]. 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, Kévin Dalleau, Esther Catherine Galbrun, Nicolas Jay, Joël Legrand, Jean Lieber, Pierre Monnin, Amedeo Napoli, Chedy Raïssi, Mohsen Sayed, Malika Smaïl-Tabbone, Yannick Toussaint.

Keywords: knowledge discovery in life sciences, biology, chemistry, medicine, pharmacogenomics and precision medicine.

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 precision medicine (pharmacogenomics). Pharmacogenomics is one main challenge for the Orpailleur team as it considers a large panel of complex data ranging from biological to medical data, and various kinds of encoded domain knowledge ranging from texts to formal ontologies.

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 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 as considered in the framework of FCA is an 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 have to be adapted, based on discussions among specialists. This adaptation process is modeled in Kasimir thanks to CBR, where semantic web technologies have been used.

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.

4.2. Other Application Domains

Participants: Emmanuelle Gaillard, Florence Le Ber, Jean Lieber, Jean-François Mari, Amedeo Napoli, Emmanuel Nauer, Sébastien Da Silva.

4.2.1. Cooking

Keywords: cooking, knowledge engineering, case-based reasoning, semantic web

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 knowledge representation, semantic web and knowledge discovery technologies. The system enables to validate 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.

4.2.2. Agronomy

Keywords: simulation in agronomy, graph model in agronomy

Research in agronomy was conducted in cooperation between Inria and INRA, within the INRA research network PAYOTE about landscape modeling. 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 [73]. Moreover, an on-going research work about the representation of farmer experience is carried on within a collaboration with IRD in Madagascar [81]. Sketches drawn by farmers were transformed into graphs and compared thanks to Formal Concept Analysis.

4.2.3. Digital Humanities

Keywords: digital humanities, semantic web, SPARQL, approximate search, case-based reasoning

Members of the Orpailleur team are collaborating with a group of researchers working in history and philosophy of science and technologies (they are located in Brest, Montpellier and Nancy). The idea is to reuse semantic web technologies for better access and better representation of their text corpora.

5. Highlights of the Year

5.1. Highlights of the Year

Classical properties of functions such as associativity, although algebraically easy to read, are hard to meaningfully interpret. In [60] Miguel Couceiro and colleagues at the University of Luxembourg (Jean-Luc Marichal, Jimmy Devillet) showed that associative and quasi-trivial operations that are non-decreasing are characterized in terms of total and weak orderings through the so-called single-peakedness property introduced in social choice theory by Duncan Black. This enabled visual interpretations of the above mentioned algebraic properties, and the enumeration of such operations led to several, previously unknown, integer sequences in Sloane’s On-Line Encyclopedia of Integer Sequences (http://www.oeis.org), e.g., `A292932`, `A292933`, and `A292934`.

6. New Software and Platforms

6.1. ARPEnTAge

Analyse de Régularités dans les Paysages : Environnement, Territoires, Agronomie
KEYWORDS: Stochastic process - Hidden Markov Models
FUNCTIONAL DESCRIPTION: ARPEnTAge is a software based on stochastic models (HMM2 and Markov Field) for analyzing spatio-temporal data-bases. ARPEnTAge is built on top of the CarottAge system to fully take into account the spatial dimension of input sequences. It takes as input an array of discrete data in which the columns contain the annual land-uses and the rows are regularly spaced locations of the studied landscape. It performs a Time-Space clustering of a landscape based on its time dynamic Land Uses (LUS). Displaying tools and the generation of Time-dominant shape files have also been defined.

- Partner: INRA
- Contact: Jean-François Mari
- URL: http://carottage.loria.fr/index_in_english.html

6.2. CarottAge

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 and a synthetic representation of temporal and spatial data. CarottAge is currently used by INRA researchers interested in mining the changes in territories related to the loss of biodiversity (projects ANR BiodivAgrim and ACI Ecoger) and/or water contamination. CarottAge is also used for mining hydromorphological data. Actually a comparison was performed with three other algorithms classically used for the delineation of river continuum and CarottAge proved to give very interesting results for that purpose.

- Participants: Florence Le Ber and Jean-François Mari
- Partner: INRA
- Contact: Jean-François Mari
- URL: http://carottage.loria.fr/index_in_english.html

6.3. CORON

KEYWORDS: Data mining - Closed itemset - Frequent itemset - Generator - Association rule - Rare itemset
FUNCTIONAL DESCRIPTION: The Coron platform is a KDD toolkit organized around three main components: (1) Coron-base, (2) AssRuleX, and (3) pre- and post-processing modules.

The Coron-base component includes a complete collection of data mining algorithms for extracting itemsets such as frequent itemsets, closed itemsets, generators and rare itemsets. In this collection we can find APriori, Close, Pascal, Eclat, Charm, and, as well, original algorithms such as ZART, Snow, Touch, and Talky-G. AssRuleX generates different sets of association rules (from itemsets), such as minimal non-redundant association rules, generic basis, and informative basis. In addition, the Coron system supports the whole life-cycle of a data mining task and proposes modules for cleaning the input dataset, and for reducing its size if necessary.

- Participants: Adrien Coulet, Aleksey Buzmakov, Amedeo Napoli, Florent Marcuola, Jérémie Bourseau, Laszlo Szathmary, Mehdi Kaytoue, Victor Codocedo and Yannick Toussaint
- Contact: Amedeo Napoli
- URL: http://coron.loria.fr/site/index.php

6.4. Tuuurbine

KEYWORD: Semantic Web
FUNCTIONAL DESCRIPTION: Tuuurbine: a Generic Ontology Guided Case-Based Inference Engine. The experience acquired since 5 years with the Taaable system conducted to the creation of a generic cased-based reasoning system, whose reasoning procedure is based on a domain ontology. This new system, called Tuuurbine, takes into account the retrieval step, the case base organization, and also an adaptation procedure which is not addressed by other generic case-based reasoning tools. Moreover, Tuuurbine is built over semantic web standards that will ensure facilities for being plugged over data available on the web. The domain knowledge is represented in an RDF store, which can be interfaced with a semantic wiki, for collaborative edition and management of the knowledge involved in the reasoning system (cases, ontology, adaptation rules).

- Contact: Emmanuel Nauer
- URL: http://tuuurbine.loria.fr/

6.5. LatViz: Visualization of Concept Lattices

- Contact: Amedeo Napoli
- URL: http://latviz.loria.fr/
- KEYWORDS: Formal Concept Analysis, Pattern Structures, Concept Lattice, Implications, Visualization

FUNCTIONAL DESCRIPTION.

LatViz is a tool allowing the construction, the display and the exploration of concept lattices. LatViz proposes some noticeable improvements over existing tools and introduces various functionalities focusing on interaction with experts, such as visualization of pattern structures for dealing with complex non-binary data, AOC-poset which is composed of the core elements of the lattice, concept annotations, filtering based on various criteria and a visualization of implications [70]. 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.

6.6. OrphaMine: Data Mining Platform for Orphan Diseases

- Contact: Chedy Raïssi
- URL: http://orphamine.inria.fr/
- KEYWORDS: Bioinformatics, data mining, biology, health, data visualization, drug development.

FUNCTIONAL DESCRIPTION.

The OrphaMine platform enables visualization, data integration and in-depth analytics in the domain of “orphan diseases”, where data is extracted from the OrphaData ontology (http://www.orpha.net/consor/cgi-bin/index.php). At present, we aim at building a true collaborative portal that will serve different actors: (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.

6.7. Siren: Interactive and Visual Redescription Mining

- Contact: Esther Catherine 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.

New features, such as a visualization of the contribution of individual literals in the queries and the simplification of queries as a post-processing, have been added to the tool, during the internship of IUT student Laëtitia Lemière.

7. New Results

7.1. Mining of Complex Data

Participants: Quentin Brabant, Miguel Couceiro, Adrien Coulet, Esther Catherine Galbrun, Nyoman Juniarta, Florence Le Ber, Joël Legrand, Pierre Monnin, Tatiana Makhalova, Amedeo Napoli, Justine Reynaud, Chedy Raïssi, Mohsen Sayed, Yannick Toussaint.

Keywords: formal concept analysis, relational concept analysis, pattern structures, pattern mining, association rule, redescription mining, graph mining, sequence mining, biclustering, skyline, aggregation

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 [77]) 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 also worked on a generic framework based on FCA in which we can define the pattern mining process at a formal level [3]. We consider several types of patterns and we are making precise the mining of complex patterns represented as sequences, trees and graphs.

We also worked on a significant extension of previous work on the discovery of skyline patterns (or "skypatterns") based on the theoretical relationships with condensed representations of patterns. We have shown how these relationships facilitate the computation of skypatterns. Thus we proposed a flexible and efficient approach to mine skypatterns using a dynamic constraint satisfaction problems (CSP) framework [30].

7.1.2. Text Mining

In the context of the PractikPharma ANR Project, we study cross-corpus training with Tree-LSTM for the extraction of biomedical relationships from texts, especially, how large annotated corpora developed for alternative tasks may improve the performance on biomedicine related tasks, for which few annotated resources are available [55]. We experiment two deep learning-based models to extract relationships from biomedical texts with high performance. The first one combines locally extracted features using a Convolutional Neural

Network (CNN) model, while the second exploits the syntactic structure of sentences using a Recursive Neural Network (RNN) architecture. Our experiments show that the latter benefits from a cross-corpus learning strategy to improve the performance of relationship extraction tasks. Indeed our approach leads to state-of-the-art performances for four biomedical tasks for which few annotated resources are available (less than 400 manually annotated sentences). This may have a particular impact in specialized domains in which training resources are scarce, because they would benefit from the training data of other domains for which large annotated corpora do exist.

In the framework of the Hybride ANR project (terminated at the end of 2016), Mohsen Sayed Hassan proposed an original machine learning approach for identifying in texts about diseases phenotypes that are not yet represented within existing ontologies [9]. The result of the extraction is used to enrich existing ontologies of the considered domain. We studied three research directions: (1) extracting relationships from texts, i.e., extracting Disease-Phenotype (D-P) relationships, (2) identifying new complex entities standing as phenotypes of a rare disease, and (3) enriching an existing rare disease ontology on the basis of the relationships previously extracted.

A collection of abstracts of scientific articles is represented as a collection of dependency graphs used for discovering relevant pieces of biomedical knowledge. We focused on the completion of rare disease descriptions, by extracting Disease-Phenotype relationships. We developed an automatic approach named SPARE$\star$, for extracting Disease-Phenotype relationships from PubMed abstracts, where phenotypes and rare diseases are previously annotated by a Named Entity Recognizer. SPARE$\star$ is the resulting hybrid approach that combines a graph-pattern based method, called SPARE, and a machine learning method (SVM). It benefits both from the good precision of SPARE and from the good recall of SVM. Finally, we applied pattern structures for classifying rare diseases and enriching an existing ontology about such diseases.

7.1.3. Mining Sequences and Trajectories

Nowadays datasets 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 finished a work on the analysis of “complex” sequential data and its usage in video games for the analysis of strategy “balance” in those games [14].

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 a preceding work [83], 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 [76]. 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 SDM in April 2017 to help foster the research on these techniques and widen their use (http://siren.mpi-inf.mpg.de/tutorial_sdm2017/main/).

7.1.5. Mining subgroups as 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) 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. 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 [1], 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 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. We continued our work on this aspect and 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). The results of this joint work with the Pesto Inria Team are published in [31].

7.1.7. Aggregation

Aggregation and consensus theory study 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 [79], [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 and methods for discovering them. Typical approaches include rough-set and FCA approaches, that we aim to extend in order to increase expressivity, applicability and readability of results. Applications of these efforts already appeared and further are expected in the context of three multidisciplinary projects, namely the "Fight Heart Failure" (research project with the Faculty of Medicine in Nancy), the European H2020 "CrossCult" project, and the "'ISIPA" (Interpolation, Sugeno Integral, Proportional Analogy) 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, the Sugeno integral is widely used in multiple criteria decision making and decision under uncertainty, for computing global evaluations of items based on local evaluations (utilities). The combination of a Sugeno integral with local utilities is called a Sugeno utility functional (SUF). A noteworthy property of SUFs is that they represent multi-threshold decision rules. However, not all sets of multi-threshold rules can be represented by a single SUF. We showed how to represent any set of multi-threshold rules as a combination of SUFs and studied their potential advantages as a compact representation of large sets of rules, as well as an intermediary step for extracting rules from empirical datasets [38], [59]. Problems related to feature selection and model elicitation where tackled in [15].

7.2. Knowledge Discovery in Healthcare and Life Sciences

Participants: Miguel Couceiro, Adrien Coulet, Kévin Dalleau, Nicolas Jay, Joël Legrand, Pierre Monnin, Amedeo Napoli, Chedy Raïssi, Mohsen Sayed, Malika Smaïl-Tabbone, Yannick Toussaint.

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 [87]. 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

This specific research takes place within two multi-disciplinary projects 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 entitled “Network-based analysis and integration”. 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)” [74] where we proposed an approach for complex graph aggregation resulting in a similarity graph between a subset of nodes. In a recent work we explored an alternative to define and efficiently compute pairwise patient similarity thanks to “Unsupervised Extremely Randomized Trees” [62].

The next challenge is to build a prediction model for each bioprofile/subgroup, once validated by clinicians, to be integrated in a decision support system. Currently, we are investigating “Statistical Relational Learning” and analogy-based methods for achieving this goal.

7.2.3. Validation of Pharmacogenomics Knowledge

A standard task in pharmacogenomics research is identifying genes that may be involved in drug response variability. Those genes are 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 latter have only used molecular network databases or biomedical literature. We

[0] “Innovations Technologiques, Modélisation et Médecine Personnalisée”
[0] “Recherche Hospitalo-Universitaire”

developed a new method that takes advantage of various linked data sources to evaluate the validity of uncertain drug-gene relationships, i.e. pharmacogenes [5]. One advantage relies on the standard implementation of linked data that facilitates the joint use of various sources and makes easier to consider features of various origins. The second advantage is related to graph mining approaches that we are using, which consider linked data in their original form, i.e. as graphs. We selected, formatted, interconnected and published an initial set of linked data sources relevant to pharmacogenomics, named PGxLOD (for “PharmacoGenomic Linked Open Data”). We applied and compared distinct numerical classification methods on these data and identified candidate pharmacogenes.

This work is a first attempt for validating state-of-the-art knowledge in pharmacogenomics, which is one objective of the ANR project “PractiKPharma” initiated in 2016 (http://practikpharma.loria.fr/). This year, we improved and enriched PGxLOD in various ways. Firstly, we wanted PGxLOD to be able to encompass pharmacogenomic knowledge of various origin, such as scientific literature, specialized databases, or Electronic Health Records (EHRs). To represent the fact that a given knowledge unit may have distinct provenances, we developed a simple ontology named PGxO (“Pharmacogenomic Ontology”) which relies on the Standard Ontology PROV-O to represent provenance. This makes possible to compare similar knowledge units that may have distinct origins [45].

7.2.4. Analysis of biomedical data annotated with ontologies

In the context of the Snowflake Inria Associate Team (at present Snowball), 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. 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 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 [29].

7.3. Knowledge Engineering and Web of Data

Participants: Emmanuelle Gaillard, Nicolas Jay, Florence Le Ber, Jean Lieber, Amedeo Napoli, Emmanuel Nauer, Justine Reynaud, Yannick Toussaint.

Keywords: knowledge engineering, web of data, definition mining, classification-based reasoning, case-based reasoning, belief revision, semantic web

7.3.1. Current Trends in Case-Based Reasoning

The Taaable project was originally created as a challenger of the Computer Cooking Contest (ICCBR Conference) [72]. Beyond its participation to the CCC challenges, the Taaable project aims at federating various research themes including case-based reasoning (CBR), knowledge discovery, knowledge engineering and belief change theory [6]. 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.

Adaptation rules have been used to manage ingredient adaptation with a restrictive set of available ingredients [43]. Three types of rule have been identified. The first type is about the substitution of ingredients belonging to a same category (e.g. dairy) by the sole available ingredient of this category (e.g. yogurt). The second type of rule is in concern with substitution, according to the role the ingredients play in the recipe, e.g. egg can be replaced by salmon in salad recipes because they are both playing the role of a protein. The last type of rules consists in removing ingredients of original recipes when they are not concerned by a rule of the first nor second type.

FCA allows the classification of objects according to the properties they share into a concept lattice. A lattice has been built from a large set a cocktail recipes according to the ingredients they use, producing a hierarchy of ingredient combinations. For example, when a cocktail 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 [43].

Two main research works were carried out about the application of CBR in medicine. Imaging, in particular in nuclear medicine, is getting more and more complex over the years. Each year, new radiotracers and machines are developed and tested. Despite this rapid evolution, few studies address the issue of image interpretation and imaging report. In [35], we show how nuclear image interpretation is improved by Tetra, a new case-based decision support system.

Cancer registries are important tools in the fight against cancer. At the heart of these registries is the data collection and coding process. Ruled by complex international standards and numerous best practices, operators are easily overwhelmed. In [48], a system is presented to assist operators in the interpretation of best medical coding practices.

Finally, an approach to adaptation based on the principles of analogical transfer applied to the formalism RDFS has been developed. 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 [2]. This is implemented within the so-called SQTRL system (for "SPARQL Query Transformation Rule Language" http://tuuurbine.loria.fr/sqtrl/) [2]. The development of SQTRL is based on a collaboration between Orpailleur team and the *Archives Henri Poincaré* (http://poincare.univ-lorraine.fr/).

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, following the increase of data published in RDF (Resource Description Framework) format and the interest in machine processable data. The 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. In the team, we are particularly interested in the "completeness of the data" viewed as their their potential to provide concept definitions in terms of necessary and sufficient conditions [69]. We have proposed a novel technique based on Formal Concept Analysis which classifies subsets of RDF data into a concept lattice [47]. This allows data exploration as well as the discovery of implication rules which are used to automatically detect "possible completions of RDF data" and to provide definitions. Moreover, this is 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.

In the same way, FCA can be used to improve ontologies associated with the Web of data. Accordingly, we proposed a method to build a concept lattice from linked data and compare the structure of this lattice with an ontology used to type the considered data [46]. The result of this comparison shows which "new axioms" can be proposed to ontology developers for guiding their design work.

7.4. Advances in Graph Theory, Clone Theory and Multiple-Valued Logic

Participants: Quentin Brabant, Miguel Couceiro, Amedeo Napoli, François Pirot, Chedy Raïssi, Jean-Sébastien Sereni.

Keywords: graph theory, graph colouring, extremal graph theory, chromatic number, multiple-valued logic, clone theory

7.4.1. Graph Theory

Proper colouring of triangle-free planar graphs is an active research topic with interesting algorithmic ramifications. It has been known for more than fifty years that such graphs can be properly 3-coloured, and Thomassen conjectured in 2007 that they actually admit an exponential number of such colourings. This statement is still wide open, and to bring forward further insight we established [75] it to be equivalent to the following:

there exists a positive real α such that whenever G is a planar graph and A is a subset of its edges whose deletion makes G triangle-free, there exists a subset A' of A of size at least $\alpha|A|$ such that $G-(A \setminus A')$ is 3-colourable. This equivalence allows us to study restricted situations, where we can prove the statement to be true.

Still on graph colouring, we demonstrated [93] a conjecture by Zhang and Whu made in 2011, that for every positive integer Δ, every K_4-minor-free graph with maximum degree Δ admits an equitable colouring with k colours whenever $k \geq \frac{\Delta+3}{2}$. A key ingredient was to *not* use the discharging method and rather exploit decomposition trees of K_4-minor-free graphs.

We also considered [88] distance colouring in graphs of maximum degree at most d and how excluding one fixed cycle of length ℓ affects the number of colours required as $d \to \infty$. For vertex-colouring and $t \geq 1$, if any two distinct vertices connected by a path of at most t edges are required to be coloured differently, then a reduction by a logarithmic (in d) factor against the trivial bound $O(d^t)$ can be obtained by excluding an odd cycle length $\ell \geq +3t$ if t is odd or by excluding an even cycle length $\ell \geq 2t+2$. For edge-colouring and $t \geq 2$, if any two distinct edges connected by a path of fewer than t edges are required to be coloured differently, then excluding an even cycle length $\ell \geq 2t$ is sufficient for a logarithmic factor reduction. For $t \geq 2$, neither of the above statements are possible for other parity combinations of ℓ and t. These results can be considered extensions of results due to Johansson (1996) and Mahdian (2000), and are related to open problems of Alon and Mohar (2002) and Kaiser and Kang (2014).

7.4.2. Multiple-Valued Logic and (Partial) Clone Theory

Clone theory was primarily motivated by the study of Boolean logic, and it currently constitutes a major subject in universal algebra, multiple-valued logic, and theoretical computer science. A clone on a set A is a class of functions $f : A^n \to A$, $n \geq 1$, that contains all projections and that is closed under compositions. Clones on a set A constitute a closure system, in fact, an algebraic lattice where meet is given by set-intersection. Clones on a 2-element set were completely classified by Emil Post. Since Post's classification several studies on clone theory have appeared and many variants and generalizations have been proposed.

As a closure system, clones can be specified within a Galois framework, namely, through the well known Pol-Inv Galois connection by the polarity between functions and the relations they preserve. This Galois connection became the main tool in several studies, in particular, in the classification of the complexity classes of CSPs ("Constraint Satisfaction Problems") [92]. Another, rather surprisingly, application of this Galois framework led to the description of of analogy-preserving Boolean classifiers [4].

Similarly, clones of partial functions (i.e., functions $f : D \to A$ for $D \subseteq A^n$) can be described by the relations its members preserve. Unlike the lattice of clones, the lattice of partial clones is of continuum cardinality even in the case of 2-element underlying sets. This shows that a complete description of this lattice is hard to attain. However, many efforts have been made towards local descriptions of this lattice, for instance, concerning the classification of its intervals that has entailed a long lasting open problem. This was settled [20] in the form of a dichotomy theorem showing that such intervals are either finite or of continuum cardinality, and we presented precise descriptions of the structure some challenging intervals in [21]. Further developments and related problems were also tackled in [11], [24], [40], [39].

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. Hydreos

Participant: Jean-François Mari.

Hydreos is a state organization -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 are used in this context, especially by agronomists of INRA (ASTER Mirecourt http://www6.nancy.inra.fr/sad-aster).

8.1.2. The Smart Knowledge Discovery Project

Participants: Jérémie Nevin, Amedeo Napoli, Chedy Raïssi.

The SKD project for "Smart Knowledge Discovery" aims at analyzing complex industrial data for troubleshooting and decision making, and is funded by "Grand Est Region". We are working with the Vize company –which is based in Nancy and specialized in visualization-based data mining– on exploratory knowledge discovery. The data which are under study are provided by the Arcelor-Mittal Steel Company and are related to the monitoring of rolling mills. Data are complex time series and the problem can be set as follows: problem statement, data access and preparation, design of adapted knowledge discovery methods based on symbolic and numerical methods, interaction with analysts, tests and validation. For the Orpailleur team, one main objective of SKD is to combine sequence mining and visualization tools for recognizing and then preventing the occurrences of defects in the outputs of the rolling mills.

8.2. National Initiatives

8.2.1. ANR

8.2.1.1. Elker (2017–2020)

Participants: Miguel Couceiro, Esther Catherine Galbrun, Amedeo Napoli, Chedy Raïssi.

The objectives of the new ELKER ANR Research Project is to study, formalize and implement the search for link keys in RDF data. Link keys generalize database keys in two independent directions, i.e. they deal with RDF data and they apply across two datasets. The goal of ELKER is to study the automatic discovery of link keys and reasoning with link keys, especially in taking an FCA point of view. One main idea is to rely on the competencies of Orpailleur in FCA for solving the problem using FCA and pattern structures algorithms, especially those related to the discovery of functional dependencies. This project involves the EPI Orpailleur at Inria Nancy Grand Est, the EPI MOEX at Inria Rhône Alpes, and LIASD at Université Paris 8.

8.2.1.2. ISTEX (2014–2017)

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 providing the research and teaching community an on-line access to scientific publications in all domains (http://www.istex.fr/istex-excellence-initiative-of-scientific-and-technical-information/). In this way, ISTEX requires a massive acquisition of documents such as journals, proceedings, corpora, and databases. The Orpailleur team was especially involved in the development of facilities for querying full-text documentation, analyzing content and extracting information. The project was carried out in collaboration with the ATILF laboratory and the INIST Institute (both located in Nancy).

8.2.1.3. PractiKPharma (2016–2020)

Participants: Adrien Coulet, Joël Legrand, Pierre Monnin, Amedeo Napoli, Malika Smaïl-Tabbone, Yannick Toussaint.

PractiKPharma for "Practice-based evidences for actioning Knowledge in Pharmacogenomics" is an ANR research project (http://practikpharma.loria.fr/) about the validation of domain knowledge in pharmacogenomics. Pharmacogenomics is interested in understanding how genomic variations related to patients have an impact on drug responses. Most of the available knowledge in pharmacogenomics (state of the art) lies in biomedical literature, with various levels of validation. An originality of PractiKPharma is to use Electronic Health Records (EHRs) to constitute cohorts of patients. These cohorts are then mined for extracting potential pharmacogenomics patterns to be then validated w.r.t. literature knowledge for becoming actionable knowledge units. More precisely, firstly we should extract pharmacogenomic patterns from the literature and secondly we should confirm or moderate the interpretation and validation of these units by mining EHRs. Comparing knowledge patterns extracted from the literature with facts extracted from EHRs is a complex task depending on the EHR language –literature is in English whereas EHRs are in French– and on knowledge level, as EHRs represent observations at the patient level whereas literature is related to sets of patients. The PractiKPharma involves three other laboratories, namely LIRMM in Montpellier, SSPIM in St-Etienne and CRC in Paris.

8.2.2. CNRS PEPS and Mastodons projects

8.2.2.1. Mastodons Projects: from HyQual to HyQualiBio (2016–2018)

Participants: Miguel Couceiro, Esther Catherine Galbrun, Tatiana Makhalova, Amedeo Napoli, Chedy Raïssi, Justine Reynaud.

The HyQual project was proposed in 2016 in response to 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 considered data mining methods are hybrid, and they combine symbolic and numerical methods for mining complex and noisy metabolic data [80]. Regarding the mining process, we are interested in the quality of the data at hand and in the discovered patterns. In particular, we check the incompleteness of the data, the quality of the extracted rules and the possible existence of redescriptions.

Initially, the project involved researchers from the EPI Orpailleur, with researchers from LIRIS Lyon, ICube Strasbourg, and INRA Clermont-Ferrand. This year, we were merged with another Mastodons project, namely QualiBioConsensus, about the “ranking of biological data using consensus ranking techniques”. The joint Mastodons project is now called “HyQualiBio”. The topics of interest for the participants are the mining of complex biological data, rankings and ties in rankings, and the search of dependencies in the web of data.

8.2.2.2. PEPS Decade

Participants: Miguel Couceiro, Esther Catherine Galbrun, Nyoman Juniarta, Amedeo Napoli, Justine Reynaud, Chedy Raïssi.

Decade stands for “Découverte et exploitation des connaissances pour l’aide à la décision en chimie thérapeutique”. The objective of the CNRS PEPS Decade project is to study the basis of knowledge system for analyzing the so-called PAINS (“Pan Assay Interference Compounds”) in chemistry. The system should rely on the knowledge possibly discovered in the data and domain knowledge and expertise. The members of the projects are interested in data mining techniques guided by constraints and preferences, “instant data mining”, subgroup discovery and exceptional model mining. All these topics were already of interest in the PEPS Prefute (2015-2016) which was about interaction and iteration in the knowledge discovery process.

The members of the Decade project are from Greyc Caen, LIFO Orléans LIRIS Lyon, Université de Tours-Blois, EPI Lacodam in Rennes and EPI Orpailleur (in association with chemists based in Caen and Orléans)

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 for achieving a 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 four real-world flagship pilots involving a total of 8 sites across Europe.

The role of the Orpailleur Team (in conjunction with the LORIA Kiwi Team) is to work on knowledge discovery and recommendation. The focus is on the mining of visitor trajectories for analysis purposes, and on the definition of a visitor profile in connection with domain knowledge for recommendation.

The numerous partners of the Orpailleur team in the CrossCult project are: 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 Not Involved in an Inria International Lab

8.4.1.1. Snowball

Title: Discovering knowledge on drug response variablity by mining electronic health records

International Partner (Institution - Laboratory - Researcher):

Stanford (United States) - Department of Medicine, Stanford Center for Biomedical Informatics Research (BMIR) - Nigam Shah

Start year: 2017

See also: http://snowball.loria.fr/

Snowball (2017-2019) is an Inria Associate Team and the continuation of the preceding Associate Team called Snowflake (2014-2016). The objective of Snowball is to study drug response variability through the lens of Electronic Health Records (EHRs) data. This is motivated by the fact that many factors, genetic as well as environmental, imply different responses from people to the same drug. The mining of EHRs can bring substantial elements for understanding and explaining drug response variability.

Accordingly the objectives of Snowball are to identify in EHR repositories groups of patients which are responding differently to similar treatments, and then to characterize these groups and predict patient drug sensitivity. These objectives are complementary to those of the PractiKPharma ANR project. Moreover, it should be noticed that Adrien Coulet has started a one-year sabbatical stay in the lab of Nigam Shah at Stanford University since September 2017.

8.4.2. Participation in International Programs

8.4.2.1. A stay at NASA Frontier Development Lab

In July 2017, Chedy Raïssi visited NASA Ames and SETI Institute as part of the Frontier Development Lab. He worked on mentoring teams and developing meaningful research opportunities, as well as supporting the work of the planetary defense community and showing the potential of this kind of applied research methodology to deliver breakthrough of significant value.

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. Recently, multiple-parameter fitting algorithms have been shown to more efficiently invert delay-Doppler datasets thus decreasing runtime while improving accuracy. However, 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.

Thus we have explored two new techniques to better automate delay-Doppler shape modeling: Bayesian optimization and deep generative models. Firstly we have implemented a Bayesian optimization routine that uses SHAPE to autonomously search the space of spin-state parameters. Bayesian optimization yielded similar spin state constraints with computer runtime reduced by a factor of 3. Secondly, the shape modeling process could be further accelerated using a deep *"generative model"* to replace or complete iterative fitting. Accordingly, we have implemented and trained a deep generative model based on different architectures of deep convolutional networks. Results are currently under analysis and future publications are in preparation.

8.4.2.2. 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 founder and previous director of LEA STRUCO, which was initiated when Jean-Sébastien was a member of LIAFA, and he is now a member of its scientific committee.

8.4.2.3. Research Collaboration with HSE Moscow

Participants: Miguel Couceiro, Adrien Coulet, Tatiana Makhalova, 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 visits Inria Nancy Grand Est every year. The collaboration is materialized by the joint supervision of students (such as the thesis of Aleksey Buzmakov defended in 2015 and the on-going thesis of Tatiana Makhalova), and the the organization of scientific events, as the workshop FCA4AI with five editions between 2012 and 2016 (see http://www.fca4ai.hse.ru).

This year, we participated in the organization of two main events: a special session about Knowledge Discovery and Formal Concept Analysis at the ISMIS Conference in Warsaw (Poland) in June 2017 (http://ismis2017.ii.pw.edu.pl/s_kd_fca.php), and the chairing of the track "General Topics of Data Analysis" at the AIST Conference in Moscow in July 2017 (6th International Conference on Analysis of Images, Social Networks, and Texts http://aistconf.org/). Finally a next edition of the seventh edition of the FCA4AI workshop is planned in July 2018 at the ECAI-IJCAI Conference to be held in Stockholm Sweden.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organization, General Chairs, Scientific Chairs

- The 25^{th} international conference on case-based reasoning (ICCBR-2017) has taken place in Trondheim (Norway) from 26 to 28 June (http://www.iccbr.org/iccbr17/). The program chairs were David W. Aha and Jean Lieber.
- Amedeo Napoli was the co-chair with Davide Ciucci and Sergei Kuznetsov of the special session "Special Session on Knowledge Discovery with Formal Concept Analysis and related formalisms (FCA4KD++)", held between June 26-29 at ISMIS Warsaw (23rd International Symposium on Methodologies for Intelligent Systems http://ismis2017.ii.pw.edu.pl/s_kd_fca.php).
- Amedeo Napoli was the co-chair with Sergei Kuznetsov of the track "General Topics of Data Analysis" at the AIST Conference in Moscow in July 2017 (6th International Conference on Analysis of Images, Social Networks, and Texts http://aistconf.org/).

- Amedeo Napoli was the general chair of BDA 2017 held between November 14-17 2017 at Inria Nancy Grand Est/LORIA, “33ième conférence sur la Gestion de Données, Principes, Technologies et Applications” https://project.inria.fr/bda2017/.

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 (AAAI, ECAI, ECML-PKDD, ESWC, ICCBR, ICDM, ICFCA, IJCAI, ISWC, KDD, SDM...), as members of editorial boards, and finally in the organization of journal special issues.

9.2. Teaching - Supervision - Juries

- All the permanent members of the Orpailleur team are involved in teaching at all levels and 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, engineers, PhD, postdoc students.
- Finally, the permanent members of the Orpailleur team are involved in HDR and thesis defenses, being thesis referees or thesis committee members.

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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
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THEME
Security and Confidentiality

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

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A4.8. - Privacy-enhancing technologies
A7.1. - Algorithms
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Other Research Topics and Application Domains:

B6.3.2. - Network protocols
B6.3.4. - Social Networks
B6.6. - Embedded systems
B9.8. - Privacy

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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 billion Euros have been spent through e-commerce in 2013 and fraud is estimated to 1.9 billion 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 cast vote without any way for the voter to notice. [0] 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 Radio-frequency identification (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 [43]. Also, anonymised data of social networks has been effectively used to identify persons by comparing data from several social networks. [0]

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

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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 [54].

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. [53]. 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 [49], 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 [44][3]. Another example is unification modulo equational theory, which is a key technique in several tools, e.g. [52]. 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 [47], which is used in several tools, e.g., *Akiss* [3], Maude-NPA [52] and Tamarin [55]. Another example is the notion of asymmetric unification [51] 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 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 include *composition results* that allow one to design protocols in a modular way [48], [46]. 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 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 also design new protocols. Application areas that seem of particular importance are:

- External hardware devices such as security APIs that allow for flexible key management, including key revocation, and their integration in security protocols. The security *fiasco* of the PKCS#11 standard [45], [50] 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

The paper [3] is listed in ACM Computing Reviews' 21st Annual Best of Computing list of notable books and articles [0] for 2016.

The voting system Belenios, developed in the Pesto and Caramba teams, has served as a basis of the development of two industrial systems (Docapost and Orange).

A 4-year ANR project on *Protocol Analysis — Combining Existing Tools* (TECAP) has been accepted. It will start in 2018 with Vincent Cheval as project leader.

6. New Software and Platforms

6.1. Akiss

AKISS: Active Knowledge in Security Protocols
KEYWORDS: Security - Verification
FUNCTIONAL DESCRIPTION: 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.

- Contact: Steve Kremer
- URL: https://github.com/akiss

6.2. Belenios

Belenios - Verifiable online voting system

[0] http://www.computingreviews.com

KEYWORD: E-voting
FUNCTIONAL DESCRIPTION: Belenios is an online voting system that provides confidentiality and verifiability. End-to-end verifiablity relies on the fact that the ballot box is public (voters can check that their ballots have been received) 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.

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

6.3. CL-AtSe

Constraint Logic based Attack Searcher
KEYWORDS: Security - Verification - Web Services
FUNCTIONAL DESCRIPTION: CL-AtSe is a Constraint Logic based Attack Searcher for security protocols and services. The main idea in CL-AtSe consists in running the protocol or set of services in all possible ways by representing families of traces with positive or negative constraints on the intruder knowledge, on variable values, on sets, etc. Thus, each run of a service step consists in adding new constraints on the current intruder and environment state, reducing these constraints down to a normalized form for which satisfiability is easily decidable, and decide whether some security property has been violated up to this point.

- Participants: Mathieu Turuani and Tigran Avanesov
- Contact: Mathieu Turuani
- URL: https://cassis.loria.fr/wiki/Wiki.jsp?page=Cl-Atse

6.4. Deepsec

DEciding Equivalence Properties in SECurity protocols
KEYWORDS: Security - Verification
FUNCTIONAL DESCRIPTION: DeepSec (DEciding Equivalence Properties 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. DeepSec implements a decision procedure to verify trace equivalence for a bounded number of sessions and cryptographic primitives modeled by a subterm convergent destructor rewrite system. The procedure is based on constraint solving techniques. Several new features are currently being developed including the possibility to verify labelled bisimilarity and session equivalence. Optimizations to improve efficiency and interface improvements are also under development.

- Contact: Vincent Cheval
- URL: https://github.com/DeepSec-prover/deepsec

6.5. Tamarin

TAMARIN prover
KEYWORDS: Security - Verification

FUNCTIONAL DESCRIPTION: 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, bilinear pairing, multisets, and exclusive-or (XOR), combined with a user-defined 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. In a joint effort, the partners wrote and published a user manual in 2016, available from the Tamarin website.

- Contact: Jannik Dreier
- URL: http://tamarin-prover.github.io/

6.6. SAPIC

SAPIC: Stateful Applied Pi Calculus
KEYWORDS: Security - Verification
FUNCTIONAL DESCRIPTION: 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 analysed using the TAMARIN prover. TAMARIN has also been extended with dedicated heuristics that exploit the form of translated rules and favor 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, and extensions of the PKCS#11 standard. SAPIC also includes support for verifying liveness properties, which are for instance important in fair exchange and contract signing protocols, as well as support for constructions useful when modelling isolated execution environments.

SAPIC has been integrated as a plugin in TAMARIN and is now part of the TAMARIN distribution.

- Contact: Steve Kremer
- URL: http://sapic.gforge.inria.fr/

6.7. TypeEquiv

A type checker for privacy properties
KEYWORDS: Security - Cryptographic protocol - Privacy
FUNCTIONAL DESCRIPTION: TypeEquiv takes as input the specification of a pair of security protocols, written in a dialect of the applied-pi calculus, together with some type annotations. It checks whether the two protocols are in equivalence or not.

- Partner: Technische Universität Wien
- Contact: Véronique Cortier

7. New Results

7.1. Modelling

7.1.1. New protocol and adversary models

Participants: Jannik Dreier, Steve Kremer, Ludovic Robin.

Symbolic models for security protocol verification, following the seminal ideas of Dolev and Yao, come in many flavors, even though they share the same ideas. A common assumption is that the attacker has complete control over the network: he can therefore intercept any message. Depending on the precise model this may be reflected either by the fact that any protocol output is directly routed to the adversary, or communications may be among any two participants, including the attacker—the scheduling between which exact parties the communication happens is left to the attacker. These two models may seem equivalent at first glance and, depending on the verification tools, either one or the other semantics is implemented. In collaboration with Babel (IIT Bombay) we show that, unsurprisingly, they indeed coincide for reachability properties. However, when we consider equivalence properties, we prove that these two semantics are incomparable. We also introduce a new semantics, where internal communications are allowed but messages are always eavesdropped by the attacker. We show that this new semantics yields strictly stronger equivalence relations and identify two subclasses of protocols for which the three semantics coincide. These results were presented at POST'17 [16].

Isolated Execution Environments (IEEs), such as ARM TrustZone and Intel SGX, offer the possibility to execute sensitive code in isolation from other, potentially 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 published and presented at EuroS&P'17 [30].

Modern security protocols may involve humans in order to compare or copy short strings between different devices. Multi-factor authentication protocols, such as Google 2-factor or 3D-secure are typical examples of such protocols. However, such short strings may be subject to brute force attacks. In collaboration with Delaune (IRISA), we propose a symbolic model which includes attacker capabilities for both guessing short strings, and producing collisions when short strings result from an application of weak hash functions. We propose a new decision procedure for analysing (a bounded number of sessions of) protocols that rely on short strings. The procedure has been integrated in the *Akiss* tool and tested on protocols from the ISO/IEC 9798-6:2010 standard. This work has been published and presented at CSF'17 [26].

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 (Univ 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 published and presented at EuroS&P'17 [17].

7.1.2. New properties

Participant: Jannik Dreier.

Industrial systems are nowadays regularly the target of cyberattacks, the most famous being Stuxnet[0]. 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 (Univ Clermont-Ferrand), Potet, and Puys (Univ 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*, they identified several design flaws in some of the different versions of these protocols. They also discussed how to efficiently model counters and timestamps in *TAMARIN*, as they are key ingredients of the analyzed protocols. This work was presented at SECRYPT'17 [32], and won a Best Student Paper Award.

7.2. Analysis

7.2.1. Analysis of equivalence properties

Participants: Vincent Cheval, Véronique Cortier, Antoine Dallon, Ivan Gazeau, Steve Kremer, Joseph Lallemand, Itsaka Rakotonirina, 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 (Univ 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. This work has been presented at CADE'17 [28].

In case of an active adversary, and a bounded number of sessions, we made several advances. The *Akiss* tool has been extended in two directions. Gazeau and Kremer, in collaboration with Baelde (LSV, ENS Cachan) and Delaune (IRISA) have extended the underlying theory and the *Akiss* tool with support for exclusive or. They analyse unlinkability in several RFID protocols and resistance to guessing attacks of several password-based protocols. This work has been presented at CSF'17 [18]. Gazeau and Kremer also extended the *Akiss* tool to analyse protocols with else branches. This is particularly useful when verifying equivalence properties, as one needs to model precisely the error messages sent out when tests fail. While ignoring these branches may often be safe when studying trace properties this is not the case for equivalence properties, as for instance witnessed by an attack on the European electronic passport. One appealing feature of our approach is that our extension re-uses the saturation procedure which is at the heart of the verification procedure of *Akiss* as a black box, without need to modify it. As a result we obtain the first tool that is able verify equivalence properties for protocols that may use xor and else branches. We demonstrate the tool's effectiveness on several case studies, including the AKA protocol deployed in mobile telephony. This result was presented at ESORICS'17 [29]. 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

[0]Stuxnet. https://en.wikipedia.org/wiki/Stuxnet

resulting implementation, SAT-Equiv, can analyze several sessions where most tools have to stop after one or two sessions. The approach has been presented at CSF'17 [20] for protocols with symmetric encryption and no else branches. Finally, Cheval, Kremer, and Rakotonirina have worked on complexity results for deciding equivalence properties and provide a decision procedure in the case of a bounded number of sessions. They showed that trace equivalence and labelled bisimilarity for a large variety of cryptographic primitives—those that can be represented by a subterm convergent destructor rewrite system— are both CoNEXP complete. Moreover, the procedure has been implemented in a new tool, *DeepSec*. Extensive experiments demonstrate that it is significantly more efficient than most other similar tools (being only slightly outperformed by SAT-Equiv in some specific examples), while at the same time raises the scope of the protocols that can be analysed. These results are currently under submission.

The previous results apply for a bounded number of sessions and may still be limited for a large number of sessions. In collaboration with Maffei and Grimm, Lallemand and Cortier have devised a novel approach [24] for proving equivalence properties. Instead of *deciding* equivalence, like for the previous approaches, they design a type system, sound w.r.t. equivalence. The resulting tool TypeEquiv can consider a bounded as well as an unbounded number of sessions, or a mix of both. It induces a significant speedup compared to previous tools for a bounded number of sessions and compares similarly to ProVerif for an unbounded number of sessions, with the advantage of a tighter treatment of bounded number of sessions. It can be applied to protocols with standard primitives and else branches.

7.2.2. Analysis of stateful security protocols

Participants: Vincent Cheval, Véronique Cortier, Jannik Dreier, Steve Kremer, Mathieu Turuani.

Many real-life protocols need to maintain a global state–such as counters, tables, or more generally, memory cells–that may be read and updated by parallel threads. Modelling such mutable, global state in protocols complicates the verification problem, in particular when analyzing an unbounded number of sessions.

The *SAPIC/TAMARIN* toolchain is one of the few tools that was designed to handle such global state. Dreier, Duménil (former intern in Pesto) 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 presented at POST'17 [27].

ProVerif is a very popular tool for the analysis of security protocols, that works very well in practice. However, in the case of protocols with global states, ProVerif typically fails in its analysis, due to its internal abstraction. Instead of designing a new ad-hoc procedure, we devise a generic transformation of the security properties queried to ProVerif. We prove the soundness of our transformation and implement it into a front-end GSVerif. Our experiments show that our front-end (combined with ProVerif) outperforms the few existing tools, both in terms of efficiency and protocol coverage. We successfully apply our tool to a dozen of protocols of the literature including a deployed voting and a payment protocol. This work is under submission.

7.2.3. Analysis of e-voting protocols

Participants: Véronique Cortier, Constantin-Catalin Dragan, Mathieu Turuani.

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 for 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 has been presented at S&P'17 [21].

Turuani and Cortier, in collaboration with Galindo (Univ Birmingham), have analysed the e-voting protocol developed by Scytl and planned to be deployed in Switzerland. The formal analysis of both privacy and individual verifiability has been conducted in ProVerif. It required to develop a crafty encoding of the security properties in order to avoid the limitations of ProVerif in the presence of global states (here, no revoting). This first encoding yielded the preliminary ideas for the GSVerif tool mentioned in the previous section. Such a formal analysis is required by the Swiss Chancellerie and has been accepted at EuroSP'18 [23].

Norway used e-voting in its last political election both in September 2011 and September 2013. The underlying protocol was also developed by Scytl. Cortier, in collaboration with Wiedling, has conducted a formal analysis (by hand) of vote privacy of this protocol, considering several corruption scenarios [13].

7.2.4. Unification in Forward-Closed Theories

Participant: Christophe Ringeissen.

In collaboration with Marshall (Univ Mary Washington, USA) and Erbatur (LMU, Germany), we investigate the unification problem in equational theories involving forward-closed convergent term rewrite systems. In the class of forward-closed theories, unification is decidable and finitary since a convergent term rewrite system has a finite forward-closure if and only if it has the finite variant property. Actually, forward-closed theories are syntactic theories admitting a terminating mutation-based unification procedure. This can be shown by reusing a mutation-based unification algorithm originally developed for equational theories saturated by paramodulation, since a forward-closed theory is indeed a sufficient condition to get soundness and completeness. Building on this fact we develop a new mutation-based unification algorithm which is simpler, with regard to conflicts and number of rules, than the first algorithm. We then use this simplified algorithm as a component to develop a new method that solves the unification problem in unions of forward-closed theories with non-disjoint theories. The resulting algorithm can be viewed as a terminating instance of a procedure initiated for hierarchical combination. This work has been presented at the workshop UNIF'17 [33].

7.2.5. Analysis of Combinations of Protocols

Participant: Jannik Dreier.

When trying to prove the security of a protocol, one usually analyzes the protocol in isolation, i.e., in a network with no other protocols. But in reality, there will be many protocols operating on the same network, maybe even sharing data including keys, and an intruder may use messages of one protocol to break another. We call that a multi-protocol attack. In this work, we tried to find such attacks using the *TAMARIN* prover. We analyzed both examples that were previously analyzed by hand or using other tools, and found novel attacks. This work was presented at FPS'17 [31].

7.3. Design

7.3.1. E-voting protocols

Participants: Véronique Cortier, Alicia Filipiak.

Building upon a recently proposed voting scheme, BeleniosRF, we design a new voting scheme that ensures both verifiability and privacy against a compromised voting machine, as well as a compromised voting server. It assumes that the voter has two devices: one computer for casting a vote and another device (typically a smartphone or a tablet) to, optionally, audit the material (a voting sheet) sent to the voter. Neither the computer nor the smartphone learns how the voter voted unless they collude. The resulting protocol has been formally analysed in ProVerif w.r.t. both verifiability and privacy. Analysing verifiability in ProVerif cannot be done directly as it would require counting. Instead, we propose a set of properties that can be handled by ProVerif and that entail verifiability. This work is one of the contribution of the thesis manuscript of Alicia Filipiak and will be submitted.

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 presented at EuroS&P'17 [22].

7.3.3. Composition and design of PKIs

Participants: Vincent Cheval, Véronique Cortier.

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 (Univ 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 has been presented at CSF'17 [19].

7.3.4. Privacy Protection in Social Networks

Participants: Younes Abid, Hector Dang-Nhu, Andrii Dychka, Abdessamad Imine, Michaël Rusinowitch, Valentin Salquebre.

In order to demonstrate privacy threats in social networks we show how to infer user preferences by random walks in a multiple graph representing simultaneously attributes and relationships links. For the approach to scale in a first phase we reduce the space of attribute values by partition in balanced homogeneous clusters. Following the Deepwalk approach, the random walks are considered as sentences. Hence unsupervised learning techniques from natural languages processing can be employed in a second phase to deduce semantic similarities of some attributes. We conduct initial experiments on real datasets to evaluate our approach. This work was presented at DEXA'17 [15].

7.3.5. Compressed and Verifiable Filtering Rules in Software-defined Networking

Participants: Haftay Gebreslasie Abreha, Michaël Rusinowitch.

In a joint project with EPI Madynes and Cynapsys, we are starting to work on the design, implementation and evaluation of multi-masked techniques for building a compressed and a verifiable filtering rules in Software Defined Networks with the possibility of distributing the workload processing among several packet filtering devices operating in parallel.

8. Bilateral Contracts and Grants with Industry

8.1. Scytl - 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 in 2016 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. The result of the analysis will be presented at the conference EuroS&P'18 [23].

8.2. Canton of Geneva - Electronic Voting Systems

Participants: Véronique Cortier, Mathieu Turuani.

The canton of Geneva has signed a contract in October 2017 with Pesto and Caramba, as well as Manifold Security (Bogdan Warinschi and David Bernhard) to design a formal and cryptographic proof of individual and universal verifiability of the protocol developed by the canton of Geneva, for a deployment in Switzerland.

8.3. Docapost - Electronic Voting Systems

Participant: Véronique Cortier.

Docapost has signed a 18-month contract in September 2017, with Pesto and Caramba, to enhance the voting solution of Docapost, in particular with respect to verifiability.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. CNRS

- CNRS PEPS INS2I 2016-2018 project ASSI *Analyse de Sécurité de Systèmes Industriels*, duration: 2 years, leader: Pascal Lafourcade (Univ Clermont-Ferrand), participant Pesto: Jannik Dreier, other participants: Marie-Laure Potet, Maxime Puys (Univ 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, other partners: ENS Cachan, Univ Luxembourg. Most protocol analysis tools are restricted to analyzing reachability properties while many security properties need to be expressed in terms of some process equivalences. 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.
- ANR TECAP *Protocol Analysis — Combining Existing Tools*, duration: 4 years, starting in 2018, leader: Vincent Cheval, other partners: ENS Cachan, Inria Paris, Inria Sophia Antipolis, IRISA, LIX. Despite the large number of automated verification tools, several cryptographic protocols (e.g. stateful protocols) still represent a real challenge for these tools and reveal their limitations. To cope with these limits, each tool focuses on different classes of protocols depending on the primitives, the security properties, etc. Moreover, the tools cannot interact with each other as they evolve in their own model with specific assumptions. The aim of this project is to get the best of all these tools, meaning, to improve the theory and implementations of each individual tool towards the strengths of the others and, to build bridges that allow the cooperations of the methods/tools. We will focus in this project on the tools CryptoVerif, EasyCrypt, Scary, ProVerif, *TAMARIN*, *Akiss* and APTE. In

order to validate the results obtained in this project, we will apply our results to several case studies such as the Authentication and Key Agreement protocol from the telecommunication networks, the Scytl and Helios voting protocols, and the low entropy authentication protocols 3D-Secure. These protocols have been chosen to cover many challenges that the current tools are facing.

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 based on 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

- 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 (Univ Oxford), and Sasa Radomirovic (Univ Dundee) on the improvement of the *TAMARIN* prover
- Collaboration with Bogdan Warinschi (Univ Bristol) on defining game-based privacy for e-voting protocols and isolated execution environments
- Collaboration with Myrto Arapinis (Univ 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 (Polytechnique Montreal) on model-checking of collaborative systems
- Collaboration with John Mullins's group (Polytechnique Montreal) on information hiding

[0] https://members.loria.fr/SKremer/files/spooc/index.html

9.4. International Research Visitors

9.4.1. Visits of International Scientists

- David Galindo (Univ Birmingham), June 2017
- Bogdan Warinschi (Univ Bristol), November 2017

10. Dissemination

10.1. Promoting Scientific Activities

V. Cortier was auditioned by the chamber of the workers in Luxembourg, on the security of electronic voting.

10.1.1. Scientific Events Selection

10.1.1.1. Program Committee Chair

- A. Imine: FPS 2017, 10th International Symposium on Foundations & Practice of Security, Nancy, October 23-25, 2017 (co-chair with J. M. Fernandez, Polytechnique Montreal, Canada)
- M. Rusinowitch: SCSS 2017, The 8th International Symposium on Symbolic Computation in Software Science, Gammarth, Tunisie, April 6-9, 2017 (co-chair with M. Mosbah, Univ Bordeaux)

10.1.1.2. Program Committee Member

- V. Cortier: E-VoteID 2018, POST 2018, E-VoteID 2017, CCS 2017, LICS 2017, SAC 2017, HotSpot 2017
- S. Kremer: Voting 2018, EuroS&P 2018, PLAS 2017, ESORICS 2017, Voting 2017, EuroS&P 2017
- C. Ringeissen: IJCAR 2018, UNIF 2018, WRLA 2018, FroCoS 2017, UNIF 2017
- M. Rusinowitch: CRISIS 2017, FPS 2017, ICISSP 2018, IWSPA 2018
- V. Cheval: TMPA 2017, SEC@SAC 2017

10.1.2. Journal

10.1.2.1. Editorial Board Member

- V. Cortier: Information & Computation, Journal of Computer Security, ACM Transactions on Privacy and Security (TOPS, previously TISSEC), Foundations and Trends (FnT) in Security and Privacy
- S. Kremer: ERCIM News

10.1.2.2. Scientific Committee Member

- L. Vigneron: Technique et Sciences Informatiques, Lavoisier

10.1.3. Invited Talks

- V. Cortier. Invited tutorial at Highlights 2017, London, UK, September 12th, 2017
- V. Cortier. Invited talk at FPS 2017, Nancy, France, October 2017
- V. Cortier. Invited talk at CIAA 2017, Marne-la-Vallée, France, June 2017
- V. Cortier. Invited talk at Workshop on the 20th Anniversary of LSV, Cachan, France, May 11th 2017
- V. Cortier. Invited tutorial at ETAPS 2017, Uppsala, Sweden, April 22nd, 2017
- V. Cortier. Invited talk at Models and Tools for Security Analysis and Proofs Workshop, affiliated with Eurocrypt 2017, Paris, France, April 29th 2017

10.1.4. Research Administration

Inria evaluation committee (S. Kremer)

Jury Junior Research Position Inria Rennes-Bretagne Atlantique (S. Kremer)

Jury Junior Research Position Inria Nancy-Grand Est (V. Cortier, committee chair)

Jury Professor at UMPC, LIP6 (V. Cortier)

Computer science commission of the Doctoral School, Univ Lorraine (L. Vigneron, chair)

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

- Licence:

  V. Cheval, Introduction to Theoretical Computer Science (Logic, Languages, Automata), 69 hours (ETD), TELECOM Nancy

  J. Dreier, Introduction to Theoretical Computer Science (Logic, Languages, Automata), 146 hours (ETD), TELECOM Nancy

- Master:

  V. Cortier, Security of flows, 20 hours, M2 Computer Science, TELECOM Nancy and Mines Nancy

  A. Imine, Security for XML Documents, 12 hours (ETD), M1, Univ Lorraine

  S. Kremer, Security Theory, 24 hours (ETD), M2 Computer science, Univ Lorraine

  C. Ringeissen, Decision Procedures for Software Verification, 18 hours (ETD), M2 Computer science, Univ Lorraine

  L. Vigneron, Security of information systems, 22.5 hours (ETD), M2 Computer science, Univ Lorraine

  L. Vigneron, Security of information systems, 24 hours (ETD), M2 MIAGE – Distributed Information Systems, Univ Lorraine

  L. Vigneron, Security of information systems, 16 hours (ETD), M2 MIAGE – Audit and Design of Information Systems, Univ Lorraine

- Summer School:

  V. Cortier and S. Kremer: Summer School on Models and Tools for Cryptographic Proofs, Nancy, June 2017

10.2.2. Supervision

- PhD in progress:

  Younes Abid, Privacy control for social networks, started in March 2015 (M. Rusinowitch)

  Antoine Dallon, Decision procedures for equivalence properties, started in November 2015 (V. Cortier and S. Delaune)

  Alicia Filipiak, Design and validation of security services for mobile platforms: smartphones and tablets, started in March 2015 (V. Cortier)

  Abreha Haftay Gebreslasie, Compressed and Verifiable Filtering Rules in Software-defined Networking, started in September 2017 (A. Lahmadi, M. Rusinowitch and A. Bouhoula)

  Charlie Jacomme, Security protocols: new properties, new attackers, new protocols, started in September 2017 (H. Comon and S. Kremer)

  Joseph Lallemand, Type systems for equivalence properties, started in September 2016 (V. Cortier)

  Itsaka Rakotonirina, Efficient verification of equivalence properties in cryptographic protocols, started in October 2017 (V. Cheval and S. Kremer)

  Ludovic Robin, Verification of cryptographic protocols using weak secrets, started in October 2014, defense scheduled early 2018 (S. Delaune and S. Kremer)

10.2.3. Juries

Examiner for Robin David, CEA and Loria (S. Kremer)

Reviewer for Ryan Stanley-Oakes, Univ Bristol (S. Kremer)

Examiner and president of the jury for Wazen Shbair, Univ Lorraine, Loria (V. Cortier)

Examiner and president of the jury for Hubert Godefroy, Univ Lorraine, Loria (V. Cortier)

Reviewer for Fabienne Eigner, Univ Saarbruecken (V. Cortier)

Reviewer for Mnacho Echenim, HDR, Univ Grenoble (M. Rusinowitch)

10.3. Popularization

- How to Explain Modern Security Concepts to your Children [11] (J. Dreier)
- Vote par Internet [41] (V. Cortier and S. Kremer)
- 2 days of debate on privacy at *Moments d'invention 2016*, organized by Grand Nancy (V. Cortier)
- booth at the *Open Government Summit* organized at Sénat (V. Cortier)
- Conference and debate at the *ISN day*, conference for teachers in computer science (V. Cortier)
- Interview for *silicon.fr* on weakening cryptosystems to allow limited access by authorities (S. Kremer)
- France 3 Lorraine radio interview on computer security (S. Kremer)
- Interview for *AFP* on electronic voting (S. Kremer)
- Interview for *AFP* and *Huffington Post* on electronic voting (V. Cortier)

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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, V. CHEVAL, S. 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.

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Publications of the year

Articles in International Peer-Reviewed Journal

[8] 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.

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[34] D. BAELDE, S. DELAUNE, I. GAZEAU, S. KREMER.*Symbolic verification of privacy-type properties for security protocols with XOR (extended version)*, Inria Nancy - Grand Est, 2017, 29, https://hal.inria.fr/hal-01533694.

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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:

A5.8. - Natural language processing
A7.2. - Logic in Computer Science
A9.4. - Natural language processing

Other Research Topics and Application Domains:

B9.5.8. - Linguistics

1. Personnel

Research Scientists

Philippe de Groote [Team leader, Inria, Senior Researcher]
Bruno Guillaume [Inria, Researcher]
Sylvain Pogodalla [Inria, Researcher]

Faculty Members

Maxime Amblard [Université de Lorraine, Associate Professor, HDR]
Guy Perrier [Université de Lorraine, Emeritus Professor, HDR]

Technical Staff

Nicolas Lefebvre [Inria]

PhD Students

Timothée Bernard [École Normale Supérieure Lyon]
Clément Beysson [Université de Lorraine]
Maria Boritchev [Inria, from Sep 2017. Intern of Université de Lorraine from Feb 2017 until Aug 2017]
Pierre Ludmann [Université de Lorraine, from Sep 2017]

Administrative Assistants

Antoinette Courrier [CNRS]
Isabelle Herlich [Inria]
Delphine Hubert [Université de Lorraine]
Martine Kuhlmann [CNRS]
Sylvie Musilli [Université de Lorraine]

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 “highest” levels.

At the level of syntax, generative grammars [35] may be seen as basic inference systems, while categorial grammars [50] are based on substructural logics specified by Gentzen sequent calculi. Finally, model-theoretic grammars [62] amount to sets of logical constraints to be satisfied.

At the level of semantics, the most common approaches derive from Montague grammars [53], [54], [55], which are based on the simply typed λ-calculus and Church’s simple theory of types [36]. 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 [57] 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 [31]. 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 [48] gave rise to sophisticated ‘dynamic’ logics [42]. 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 [67]. This correspondence is the keystone of the syntax-semantics interface of modern type-logical grammars [56]. It also motivated the definition of our own Abstract Categorial Grammars [4].

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 [6], [65], [66], [60], [49], [61].

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 [64], [32], [33], [63], and the related theories of functional control operators [38], [39].

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 [45] and graph rewriting [2] as models of natural language syntax. This includes the development of grammars for French [59], [2], 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 grammars for French, and provide our parsers 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 research program of Sémagramme aims 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 [41], 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.

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).

- Participants: Philippe De Groote, Jiri Marsik, Sylvain Pogodalla and Sylvain Salvati
- Contact: Sylvain Pogodalla
- Publications: A syntax-semantics interface for Tree-Adjoining Grammars through Abstract Categorial Grammar - ACGTK: un outil de développement et de test pour les grammaires catégorielles abstraites - Discourse Modeling with Abstract Categorial Grammars - On the expressive power of Abstract Categorial Grammars: Representing context-free formalisms - Towards abstract categorial grammars
- URL: http://calligramme.loria.fr/acg/

5.2. Dep2pict

KEYWORDS: Syntactic analysis - Semantics

FUNCTIONAL DESCRIPTION: Dep2pict is a program for drawing graphical representation of dependency structures of natural language sentences. Dep2pict takes into account the modified format mixing surface and deep syntactic information used in deep-sequoia.

- Contact: Bruno Guillaume
- URL: http://dep2pict.loria.fr/

5.3. Grew

Graph Rewriting
KEYWORDS: Semantics - Syntactic analysis - Natural language processing - 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).

- Contact: Bruno Guillaume
- URL: http://grew.loria.fr/

5.4. LEOPAR

KEYWORD: Parsing
FUNCTIONAL DESCRIPTION: Parser for natural language based on interacation grammars

- Participants: Bruno Guillaume, Guillaume Bonfante and Guy Perrier
- Contact: Bruno Guillaume

5.5. ZombiLingo

KEYWORDS: Syntactic analysis - Natural language processing - Lexical resource - Collaborative science
FUNCTIONAL DESCRIPTION: ZombiLingo is a prototype of a GWAP where gamers have to give linguistic information about the syntax of natural language sentence, currently in French, and later to other languages.

- Authors: Bruno Guillaume, Karën Fort, Nicolas Lefebvre and Valentin Stern
- Contact: Karën Fort
- URL: http://zombilingo.org/

5.6. Platforms

5.6.1. SLAMtk

SLAMtk is a processing chain of transcriptions of interviews for the SLAM project (see Section 7.1.1). In particular, it products of a full anonymized and randomized version of the resources. Some extensions, based on Distagger (tagging of disfluencies) and MElt (tagging of part-of-speech and lemmas), have been implemented in order to run linguistic analyses. 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. 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 [40], [34], [28], [52]. Frames consist 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 [51].

Following up on our previous work [46], [47] based on Hybrid Logic (HL) [30], [27] on linking Frames and truth-logical semantics, 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.) [7].

6.2. Discourse Dynamics

Participants: Maxime Amblard, Timothée Bernard, Clément Beysson, Maria Boritchev, Philippe de Groote, Bruno Guillaume.

6.2.1. Dynamic Generalized Quantifiers

We have started a classification of the (French) determiners according to the dynamic properties of the generalized quantifiers they denote [12], [17].

Following Groenendijk and Stokhof [43], we say that a generalized quantifier is *internally dynamic* in case the dynamic binders occurring in its restriction have the capacity of binding material that occurs in their scopes. We also say that a generalized quantifier is *externally dynamic* in case the dynamic binders occurring in both its arguments have the capacity of binding material that occur in the continuation of the discourse. In addition to these notions of internal and external dynamicity, we consider a third notion that we call *intrinsic dynamicity*. We say that a generalized quantifier is intrinsically dynamic in case it introduces new referent markers and makes them available to the continuation of the discourse.

Using these three notions, we have defined three classes of dynamic generalized quantifiers, which fairly correspond to the notions of specific (e.g., *the*, *this*, *his*), general (e.g., *a*, *some*, *another*), and quantificational determiners (e.g., *every*, *no*). We then have shown how the dynamic generalized quantifiers belonging to these three classes may be formalized using the continuation-based approach introduced in [5].

6.2.2. Dialogue Modeling

Studying dialogical interactions is a major subject in natural language processing, since dialogues represent the basis of human communication. Addressing this problem requires relating approaches from fields such as semantics, pragmatics, and, more generally, logic, and cognition. We have presented a compositional dynamic model of questions and answers mechanisms in a dialogical setting. We address dialogical and lexical issues starting from the formal definitions of frame semantics given in [7]. We achieve compositionality and dynamicity in our model by constructing it on top of concepts inherited from Type Theoretical Dynamic Logic [5]. We introduce control in the common (accessible to all participants of a dialogue) context of a conversation by formulating the concept of dialogical context and elaborating corresponding storage operations. We apply our model to real non-controlled examples of dialogical interactions provided by the Schizophrenia and Language, Analysis and Modeling corpus [29]. The linguistic analysis of dialogues between patients with schizophrenia and psychologists has revealed specific language-driven manifestations of cognitive dysfunction. This approach to dialogue modeling in a dynamic framework allowed us to develop tools to handle specifics of dialogical interactions on top of already existing methods for general discourse.

6.2.3. Discourse Structure

A text as a whole must exhibit some coherence that makes it more than just a bag of sentences. This coherence hinges on the discourse relations (DRs). The latter express the articulations between the different pieces of information of the text. There is still debate about the number and the nature of these DRs. Yet, typical DRs include `Contrast`, `Consequence`, or `Explanation`. Using a discourse connective (*because*, *instead*, *although*) is usually the most direct and reliable way to express a DR. These lexical items have specific syntactic, semantic, and pragmatic properties. In particular, one can often observe a mismatch between the arguments of a DR and the (syntactic) ones of the connective lexicalizing it. It happens in configurations in which the argument of the DR does not directly correspond to syntactic argument of the discourse marker. In (1), for instance, the second argument of the `Explanation` relation is not the whole conditional, its antecedent, nor its consequent. But it is the possibility of the conditional, paraphrasable by *she might miss her train*. The discourse argument is here presupposed by the conditional (i.e., the syntactic argument).

1. Mary is worried because if there is too much delay, she will miss her train.
2. John did not come to the party although Mary said he was already back in town.

Another common case occurs when an attitude verb (*think*, *believe*) or a verb of report (*say*, *tell*) is used evidentially as in (2). In such cases, the contrast expressed by the writer holds between *John did not come to the party* and *he was already back in town*. The main function of the evidential (*Mary said ...*) is to introduce the argument of a DR without being itself part of the discourse structure.

Whereas DRs have two arguments, some discourse markers, such as adverbial connectives (*so*, *otherwise*), have only one syntactic argument. It then seems natural to use an anaphoric mechanisms to describe how the other argument of the DR they lexicalise is determined from the context. We extended this idea to all connectives and showed how this view can explain most usual cases of mismatch. Additionally, considering that discourse arguments are implicit semantic objects akin to the events introduced in the Davidsonian theory, it is possible to implement this proposal in Type Theoretic Dynamic Logic, without the need of a syntactic parse above the sentence level, and in a strictly compositional way, using continuations.

6.3. Common Basic Resources

Participants: Maxime Amblard, Clément Beysson, Philippe de Groote, Bruno Guillaume, Guy Perrier, Sylvain Pogodalla, Nicolas Lefebvre.

6.3.1. Crowdsourcing Complex Language Resources

Using a Wikipedia corpus, we showed that participants in a game with a purpose can produce quality dependency syntax annotations [44]. In [15], we have been considering a more complex corpus of scientific language. We ran an experiment aiming at evaluating the production of the participants of the game, and compared it to a gold corpus, annotated and adjudicated by experts of the domain.

We also ran two surveys on ZombiLingo's players, in order to better understand who they are and what their motivations in playing the game are, and improve the participation in the game [14].

6.3.2. Universal Dependencies

We participated to the development of new versions of the French part of the Universal Dependencies project (UD, http://universaldependencies.org/). Version 2.0 [58] was released in March 2017. In this version, a new French corpus *UD_French-Sequoia* was added. We built this corpus with an automatic conversion (using the Grew software) from the data built in the Sequoia project.

Version 2.1 [24] was released in November 2017. The conversion process, using Grew, was applied to the FrenchTreebank corpus, and led to a new corpus in Universal Dependencies: *UD_French-FTB*. In version 2.1, we worked on the harmonization of the subset of French treebanks. The Grew software was used to explore, to check consistency, and to systematically correct the data.

The "enhanced dependencies" sketched in the UD 2.0 guidelines is a promising attempt in the direction of deep syntax, an abstraction of the surface syntax towards semantics. In [13] (collaboration with Marie Candito and Djamé Seddah), we proposed to go further and enrich the enhanced dependency scheme along two axes: extending the cases of recovered arguments of non-finite verbs, and neutralizing syntactic alternations. Doing so leads to both richer and more uniform structures, while remaining at the syntactic level, and thus rather neutral with respect to the type of semantic representation that can be further obtained. We implemented this proposal in two UD treebanks of French, using deterministic graph rewriting rules. Evaluation on a 200-sentence gold standard showed that deep syntactic graphs can be obtained from surface syntax annotations with a high accuracy. Among all semantic arguments of verbs in the gold standard, 13.91% are impacted by syntactic alternation normalization, and 18.93% are additional edges corresponding to deep syntactic relations.

In [16], we present a reflection on the annotation of written French corpora in syntax and semantics. This reflection is the result of work carried out on the SEQUOIA and the UD-FRENCH corpora.

6.3.3. FR-Fracas

There are two major levels of processing that are significant in the use of a computational semantic frameworks: semantic composition, for the construction of meanings, and inference, either to exploit those meanings, or to assist the determination of contextually sensitive aspects of meanings. FraCas is an inference test suite for evaluating the inferential competence of different NLP systems and semantic theories. Providing an implementation of the inference level was beyond the scope of FraCaS, but the test suite nevertheless provides an overview of a useful and theory- and system-independent semantic tool [37].

There currently exists a multilingual version of the resource for Farsi, German, Greek, and Mandarin. We started the translation into French. 10% of the resource has been translated so far as a testbed, in order to setup guidelines for the translations. We plan to complete the translation following these guidelines and use it as an experimental tool.

7. Partnerships and Cooperations

7.1. Regional Initiatives

7.1.1. 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. The SLAM project aims at exploring the specific manifestation of disorders in conversational speech. This is an interdisciplinary research, both empirical and theoretical, from several domains, namely psychology, philosophy, linguistic, and computer science.

After having built building a corpus of pathological uses of language [9], the first transcriptions of pathological interviews have been analyzed [8]. A processing chain was implemented for disfluences and part-of-speech. We have focused on implementing the treatment of lexicographical issues, and proposed an interface for SDRT-annotations. We also started to collect new data with new patients at the Centre Médical d'Aix-en-Provence, and to re-implement the SLAMtk tool.

The SLAM project was supported by the MSH–Lorraine, USR 3261, the region Grand Est, and the Université de Lorraine. We have organized the fourth workshop (In)Coherence of Discourse which gathered linguists, psychologists, and computer scientists in March 2017.

7.2. National Initiatives

7.2.1. DGLFLF (Délégation générale à la langue française et aux langues de France)

7.2.1.1. PLURAL

Participants: Bruno Guillaume [coordinator], Nicolas Lefebvre.

The objective of the PLURAL project is to build linguistic resources with GWAPs (Game With A Purpose) for poorly endowed languages. Unlike other languages, poorly endowed languages lack of freely available raw corpora. The goal of the PLURAL project is to provide a web inferface to gather corpora in poorly endowed languages of France. First target languages are Alsacian and Guadeloupean creole. The main difficulty is to take into account orthographic diversity and regional diversity for these languages.

Partners of the PLURAL projet are: Université Paris-Sorbonne (Karën Fort, Alice Millour, André Thibault) and Université de Strasbourg (Delphine Bernhard).

Nicolas Lefebvre is engineer in the PLURAL project from October 2017 to March 2018.

7.3. International Initiatives

7.3.1. Inria International Partners

7.3.1.1. Informal International Partners

Maxime Amblard have started discussing with the Centre for Linguistic Theory and Studies in Probability (CLASP, University of Gothenburg, Sweden), about computational treatments of dialogues of patients with schizophrenia. We have common issues about the management such corpora and about the modeling of such interactions. As for now, ongoing discussions have not yet been turned into a formal project.

7.4. International Research Visitors

7.4.1. Visits to International Teams

7.4.1.1. Research Stays Abroad

Timothée Bernard visited New York University, USA, from September 1st to December 15th, 2017.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Events Organisation

8.1.1.1. General Chair, Scientific Chair

- Maxime Amblard: General chair of (In)Coherence of Discourse 4, March 2017, Université de Lorraine.

- Bruno Guillaume: General chair of "Acor4French: les corpus annotés du français", workshop of the TALN conference.

8.1.2. Scientific Events Selection

8.1.2.1. Chair of Conference Program Committees

- Philippe de Groote: co-chair of MoL 2017*15th Meeting on the Mathematics of Language* [20].
- Sylvain Pogodalla: co-chair of FG 2017*22nd Conference on Formal Grammar* [19].

8.1.2.2. Reviewer

- Maxime Amblard: (In)Coherence of Discourse 4, ACL2017, TALN 17, traitement automatique des langues, and RECITAL17 Rencontre des Étudiants Chercheurs en Informatique pour le Traitement Automatique des Langues, journée EGC-IA.
- Philippe de Groote: (In)Coherence of Discourse 4, MoL 2017, FG 2017, IWCS 2017.
- Bruno Guillaume: ACL2017, LREC2018.
- Sylvain Pogodalla: (In)Coherence of Discourse 4, TAG+13*13th International Workshop on Tree Adjoining Grammars and Related Formalisms*.

8.1.3. Journal

8.1.3.1. Member of Editorial Boards

- Maxime Amblard: Member of the editorial board of the journal *Traitement Automatique des Langues*, in charge of the final editing process.
- 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.

8.1.3.2. Reviewer - Reviewing Activities

- Maxime Amblard: Journal of Language, Logic and Information, *Traitement Automatique des Langues*.
- Philippe de Groote: Journal of Language, Logic and Information, Logical Methods in Computer Science.
- Sylvain Pogodalla: Journal of Language, Logic and Information, Mathematical Structures in Computer Science, *Traitement Automatique des Langues*;

8.1.4. Invited Talks

- Maxime Amblard:
  - A Formal Account of Disorders in Dialogues, CLASP seminar, November 2017, University of Gothenburg, Sweden [8].
  - Table ronde "TAL et médical", TALN 2017, June 2017, Orléans.
  - Le discours des schizophrènes par la formalisation langagière, interpréter les troubles de la pensée par les troubles du langage, Séminaire C2S, June 2017, Université de Reims [9].
  - Modélisation sémantique de la langue, une mise en pratique, séminaire SIESTE, computer science department, ENS Lyon, March 2017, Lyon [22].
- Timothée Bernard:
  - A Montagovian semantics for discourse connectives, NYU Semantics Group, October 2017, New York, USA.
  - Negative events, joint work with Lucas Champollion, NYU Semantics Group, December 2017, New York, USA.
- Sylvain Pogodalla: Tutorial at FSMNLP 2017 & TAG+13 [26], Umeå, Sweden, September 2017.

- Guy Perrier: invited talk in the seminar of the TEXTE team (LIRMM, Montpellier), March 2017.

8.1.5. Leadership within the Scientific Community

- Philippe de Groote: 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: 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: member of the scientific council of the LIRMM, *Laboratoire d'Informatique, de Robotique et de Microélectronique de Montpellier*; member of the scientific council of the AREN e-FRAN project, *ARgumentation Et Numérique*.
- Sylvain Pogodalla: external reviewer for CIMI LabEx, expert for the Research Executive Agency (REA) of the EU.
- Guy Perrier: external rapporteur on the scientific activity of Prof François Lareau (Université de Montréal, Canada) for his promotion as "professeur agrégé".

8.1.7. Research Administration

- Maxime Amblard:
  - Member of *conseil scientifique de l'Université de Lorraine*.
  - Standing invitee at the "pôle scientifique" AM2I of Université de Lorraine.
  - Member of the standing committee of the *conseil de laboratoire du Loria*.
  - Member of the board of the *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.
  - Member of the McF selection committee 4373 (section 7 and 27), Université Paris Sorbonne.
- Philippe de Groote:
  - Member of the *bureau du comité des projets d'Inria Nancy – Grand Est*.
- 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.
  - Member of the Comipers (Inria committee for PhD and Post-doctoral selection).

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

Licence:

Maxime Amblard, Ingénierie de la langue, 25h, L3, Université de Lorraine, France.

Maxime Amblard, Panorama du TAL, 2h, L1, Université de Lorraine, France.

Timothée Bernard, Algorithmique (TD), 24h, L3, Université Paris Diderot – Paris 7, France.

Clement Beysson, C2I, 18h, L1, Université de Lorraine, France.

Clement Beysson, Linguistique, 14h, L2, Université de Lorraine, France.

Clement Beysson, Représentation Avancé de Donnée, 25h, L2, Université de Lorraine, France.

Clement Beysson, Ingénierie de la langue, 10h, L3, Université de Lorraine, France.

Pierre Ludmann, TD Tronc Commun d'Informatique I, 20h, 1st year Formation Ingénieur Civil, Mines Nancy, France.

Master:

Maxime Amblard, Formalisms: from Syntax to Discourse (english), 50h, M2, Université de Lorraine, France.

Maxime Amblard, Research methodology (english), 10h, M2, Université de Lorraine, France.

Maxime Amblard, Remise à niveau TAL (english), 4h, M2, Université de Lorraine, France.

Maxime Amblard, initiation au TAL, 30h, M1, Université de Lorraine, France.

Maxime Amblard, Programming for NLP (english), 44h, M1, Université de Lorraine, France.

Philippe de Groote, Formal logic, 35h, M2, Université de Lorraine, France.

Philippe de Groote, Computational structures and logics for natural language modeling, 18h, M2, Université Paris Diderot – Paris 7, France.

Bruno Guillaume, Remise à niveau TAL (english), 9h, M2, Université de Lorraine, France.

Bruno Guillaume, Linguistic Resources TAL (english), 15h, M2, Université de Lorraine, France.

Sylvain Pogodalla, Formal Languages, 24h, M2, Université de Lorraine, France.

8.2.2. Supervision

PhD in progress:

Clement Beysson, *Quantificateurs généralisés dynamiques pour l'analyse discursive*, since September 2015, Philippe de Groote and Bruno Guillaume.

Maria Boritchev, *Dialogue Dynamics Modeling in the Simple Theory of Types*, since September 2017, Maxime Amblard and Philippe de Groote.

Pierre Ludmann, *Construction dynamique des structures discursives*, since September 2017, Philippe de Groote and Sylvain Pogodalla.

8.2.3. Juries

Maxime Amblard was member of the jury of the master thesis of the master NLP (6 students).

Sylvain Pogodalla was member of the jury of the PhD thesis of Rapaël Salmon, *Natural Language Generation Using Abstract Categorial Grammars* July 10, 2017, Paris Diderot – Paris 7 University.

Sylvain Pogodalla was member of the jury of the *Prix de la thèse 2017* of the *Association pour le Traitement automatique des Langues (ATALA)*.

8.3. Popularization

- Maxime Amblard:

- Vice head of the editorial board of interstices)i(, a French magazine popularizing computer sciences.
- Several publication about algorithms, AI and NLP for interstices)i(.
- Winner of a Blaise Pascal Foundation grant for a project to create a happy families game (*jeu des sept familles*) based on computer science sub-fields and scientists.

- Bruno Guillaume: interviewed by the large audience scientific newspaper *Sciences & Avenir* (January 2017) for the article *Pour aidez la recherche, jouez !*

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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/.

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Publications of the year

Articles in International Peer-Reviewed Journal

[7] L. Kallmeyer, R. Osswald, S. Pogodalla.*Quantification in Frame Semantics with Binders and Nominals of Hybrid Logic*, in "Journal of Language Modelling", 2017, vol. 5, n^{o} 2 [*DOI :* 10.15398/JLM.V5I2.147], https://hal.inria.fr/hal-01417853.

Invited Conferences

[8] M. Amblard.*A Formal Account of Disorders in Dialogues*, in "CLASP seminar", Gothenburg, Sweden, November 2017, p. 1-158, https://hal.inria.fr/hal-01655817.

[9] M. AMBLARD.*Le discours des schizophrènes par la formalisation langagière, interpréter les troubles de la pensée par les troubles du langages*, in "2017 - Séminaire C2S", Reims, France, June 2017, p. 1-109, https://hal.inria.fr/hal-01655828.

[10] M. BORITCHEV.*On Politics and Argumentation*, in "MALOTEC", Nancy, France, March 2017, https://hal.archives-ouvertes.fr/hal-01666416.

International Conferences with Proceedings

[11] T. BERNARD.*Factuality information as sets of probabilities*, in "24ème conférence sur le Traitement Automatique des Langues Naturelles", Orléans, France, articles courts, June 2017, vol. 2, https://hal.inria.fr/hal-01560547.

[12] C. BEYSSON.*Determiners and dynamic generalised quantifiers*, in "TALN 2017 - Traitement Automatique des Langues Naturelles", Orléans, France, H. FLAMEIN, Y. PARMENTIER (editors), June 2017, p. 81-93, https://hal.archives-ouvertes.fr/hal-01651749.

[13] M. CANDITO, B. GUILLAUME, G. PERRIER, D. SEDDAH.*Enhanced UD Dependencies with Neutralized Diathesis Alternation*, in "Depling 2017 - Fourth International Conference on Dependency Linguistics", Pisa, Italy, September 2017, https://hal.inria.fr/hal-01625466.

[14] K. FORT, B. GUILLAUME, N. LEFÈBVRE.*Who wants to play Zombie? A survey of the players on ZOMBILINGO*, in "Games4NLP 2017 - Using Games and Gamification for Natural Language Processing", Valencia, Spain, Symposium Games4NLP, April 2017, 2, https://hal.inria.fr/hal-01494043.

National Conferences with Proceeding

[15] K. FORT, B. GUILLAUME, N. LEFÈBVRE, L. RAMÍREZ, M. REGNAULT, M. COLLINS, O. GAVRILOVA, T. KRISTANTI.*Towards (more) complex corpora annotation using a game with a purpose : the case of scientific language*, in "Traitement Automatique des Langues Naturelles (TALN)", Orléans, France, June 2017, https://hal.archives-ouvertes.fr/hal-01583863.

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Conferences without Proceedings

[17] C. BEYSSON, S. BLIND, P. DE GROOTE, B. GUILLAUME.*Generalized Quantifiers and Dynamicity — preliminary results —*, in "QUAD2017 - QUantifiers And Determiners as part of ESSLLI 2017", Toulouse, France, July 2017, p. 1-6, https://hal.archives-ouvertes.fr/hal-01651668.

Books or Proceedings Editing

[18] M. AMBLARD, M. MUSIOL, M. REBUSCHI, M.-H. PIERRE, S. JOKULSSON (editors). *(In)Coherence of discourse 4*, Published by the authors, March 2017, p. 1-19, https://hal.inria.fr/hal-01655957.

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[20] M. KANAZAWA, P. DE GROOTE, M. SADRZADEH (editors). *MOL 2017, the 15th Meeting on the Mathematics of Language: Proceedings of the conference*, Association for Computational Linguistics, London, United Kingdom, 2017, https://hal.inria.fr/hal-01654605.

Scientific Popularization

[21] M. AMBLARD.*Regard sur « Le temps des algorithmes »*, in "Interstices", January 2017, https://hal.inria.fr/hal-01466800.

[22] M. AMBLARD.*Modélisation sémantique de la langue, une mise en pratique*, in "SIESTE 2017 - Séminaire d'Informatique pour les Etudiants, Scientifiques, et Tous ceux que l'informatique intéresse à l'ENS Lyon", Lyon, France, February 2017, p. 1-77, https://hal.inria.fr/hal-01655840.

[23] M. BORITCHEV.*Grande L3 deviendra mini-chercheuse*, in "Séminaire SIESTE", Lyon, France, February 2017, https://hal.archives-ouvertes.fr/hal-01666417.

Other Publications

[24] H. LEUNG, C. Y. LI, J. LI, K. LI, N. LJUBEŠIĆ, O. LOGINOVA, O. LYASHEVSKAYA, T. LYNN, V. MACKETANZ, A. MAKAZHANOV, M. MANDL, C. MANNING, C. MĂRĂNDUC, D. MAREČEK, K. MARHEINECKE, H. MARTÍNEZ ALONSO, A. MARTINS, J. MAŠEK, Y. MATSUMOTO, R. MCDONALD, G. MENDONÇA, N. MIEKKA, A. MISSILÄ, C. MITITELU, Y. MIYAO, S. MONTEMAGNI, A. MORE, L. MORENO ROMERO, S. MORI, B. MOSKALEVSKYI, K. MUISCHNEK, K. MÜÜRISEP, P. NAINWANI, A. NEDOLUZHKO, G. NEŠPORE-BĒRZKALNE, L. NGUYỄN THỊ, H. NGUYỄN THỊ MINH, V. NIKOLAEV, H. NURMI, S. OJALA, P. OSENOVA, R. ÖSTLING, L. ØVRELID, E. PASCUAL, M. PASSAROTTI, C. PEREZ, G. PERRIER, S. PETROV, J. PIITULAINEN, E. PITLER, B. PLANK, M. POPEL, L. PRETKALNIŅA, P. PROKOPIDIS, T. PUOLAKAINEN, S. PYYSALO, A. RADEMAKER, L. RAMASAMY, T. RAMA, V. RAVISHANKAR, L. REAL, S. REDDY, G. REHM, L. RINALDI, L. RITUMA, M. ROMANENKO, R. ROSA, D. ROVATI, B. SAGOT, S. SALEH, T. SAMARDŽIĆ, M. SANGUINETTI, B. SAULĪTE, S. SCHUSTER, D. SEDDAH, W. SEEKER, M. SERAJI, M. SHEN, A. SHIMADA, D. SICHINAVA, N. SILVEIRA, M. SIMI, R. SIMIONESCU, K. SIMKÓ, M. ŠIMKOVÁ, K. SIMOV, A. SMITH, A. STELLA, M. STRAKA, J. STRNADOVÁ, A. SUHR, U. SULUBACAK, Z. SZÁNTÓ, D. TAJI, T. TANAKA, T. TROSTERUD, A. TRUKHINA, R. TSARFATY, F. TYERS, S. UEMATSU, Z. UREŠOVÁ, L. URIA, H. USZKOREIT, S. VAJJALA, D. V. NIEKERK, G. V. NOORD, V. VARGA, E. VILLEMONTE DE LA CLERGERIE, V. VINCZE, L. WALLIN, J. N. WASHINGTON, M. WIRÉN, T. WONG, Z. YU, Z. ŽABOKRTSKÝ, A. ZELDES, D. ZEMAN, H. ZHU, J. NIVRE, Ž. AGIĆ, L. AHRENBERG, L. ANTONSEN, M. J. ARANZABE, M. ASAHARA, L. ATEYAH, M. ATTIA, A. ATUTXA, L. AUGUSTINUS, E. BADMAEVA, M. BALLESTEROS, E. BANERJEE, S. BANK, V. BARBU MITITELU, J. BAUER, K. BENGOETXEA, R. A. BHAT, E. BICK, V. BOBICEV, C. BÖRSTELL, C. BOSCO, G. BOUMA, S. BOWMAN, A. BURCHARDT, M. CANDITO, G. CARON, G. CEBIROĞLU ERYIĞIT, G. G. A. CELANO, S. CETIN, F. CHALUB, J. CHOI, S. CINKOVÁ, Ç. ÇÖLTEKIN, M. CONNOR, E. DAVIDSON, M. DE MARNEFFE, V. DE PAIVA, A. DIAZ DE ILARRAZA, P. DIRIX, K. DOBROVOLJC, T. DOZAT, K. DROGANOVA, P. DWIVEDI, M. ELI, A. ELKAHKY, T. ERJAVEC, R. FARKAS, H. FERNANDEZ ALCALDE, J. FOSTER, C. FREITAS, K. GAJDOŠOVÁ, D. GALBRAITH, M. GARCIA, M. GÄRDENFORS, K. GERDES, F. GINTER, I. GOENAGA, K. GOJENOLA, M. GÖKIRMAK, Y. GOLDBERG, X. GÓMEZ GUINOVART, B. GONZÁLES SAAVEDRA, M. GRIONI, N. GRŪZĪTIS, B. GUILLAUME, N. HABASH, J. HAJIČ, J. HAJIČ JR., L. HÀ MỸ, K. HARRIS, D. HAUG, B. HLADKÁ, J. HLAVÁČOVÁ, F. HOCIUNG, P. HOHLE, R. ION, E. IRIMIA, T. JELÍNEK, A. JOHANNSEN, F. JØRGENSEN, H. KAŞIKARA, H. KANAYAMA, J. KANERVA, T. KAYADELEN, V. KETTNEROVÁ, J. KIRCHNER, N. KOTSYBA, S. KREK, V. LAIPPALA, L. LAMBERTINO, T. LANDO, J. LEE, P. LÊ HỒNG, A. LENCI, S. LERTPRADIT.*Universal Dependencies 2.1*, 2017, LINDAT/CLARIN digital library at the Institute of Formal and Applied Linguistics (ÚFAL), Faculty of Mathematics and Physics, Charles

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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

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Project-Team SPHINX

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

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1. Personnel

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Julie Valein [Univ de Lorraine, Associate Professor]

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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 the coupling between the subsystems into account.

(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 fishes 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). 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 have constituted 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 stone destruction, osteoporosis diagnosis, etc.), telecommunications (in urban or submarine environments, optical fibers, etc.), aeronautics (target 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 solving 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 [93], [88], [68], and almost all mathematical results on such FSIS have been obtained in the last twenty years.

The most studied FSIS is the problem modeling a **rigid body moving into a viscous incompressible fluid** ([51], [47], [87], [57], [62], [90], [92], [76], [60]). Many other FSIS have been studied as well. Let us mention [78], [65], [61], [50], [40], [56], [41], [58] for different fluids. 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). The obtained coupled FSIS is a complex system and its study raises several difficulties. The main one comes from the fact that we gather two systems of different nature. Some studies have been performed for approximations of this system: [45], [40], [71], [52], [43]). Without approximations, the only known results [48], [49] is done with very strong assumptions on the regularity of the initial data. Such assumptions are not satisfactory but seem inherent to this coupling between two systems of different natures. 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 ([85]). This permits to start the mathematical study of a challenging problem: understanding the locomotion mechanism of aquatic animals. This is related to control or stabilization problems for FSIS. Some first results in this direction were obtained in [66], [42], [81].

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 [67] or Kaltenbacher, Neubauer, and Scherzer [69]). 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 provide 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 to noise, disturbances and discretization. A wide class of methods is based on optimization techniques.

We can split our research in inverse problems into two classes 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 seen 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 [35], [59], [63], [89] for the design of feedback controllers), an input (for instance source inverse problems [32], [44], [53]) or a parameter of the system. These problems are generally ill-posed and many regularization approaches have been developed. Among the different methods used for identification, let us mention optimization techniques ([46]), specific one-dimensional techniques (like in [36]) or observer-based methods as in [73].

   In the last few years, we have developed observers to solve initial data inverse problems for a class of linear systems of infinite dimension. Let us recall that observers, or Luenberger observers [72], have been introduced in automatic control theory to estimate the state of a dynamical system of finite dimension from the knowledge of an output (for more references, see for instance [77] or [91]). Using observers, we have proposed in [80], [64] an iterative algorithm to reconstruct initial data from partial measurements for some evolution equations.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 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 [38], [37].

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 Liège (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. 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. The members of SPHINX have already worked on these three families of numerical methods for FSIS systems with rigid bodies (see e.g. [84], [70], [86], [82], [83], [74]).
- **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) [39], [54], [55] 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 us 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 at high frequency [34], [33]), 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 problem *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 media 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 (for instance robotswim) but also for medical objectives. The website http://www.robotic-fish.net/ presents a list of several robotic fish that have been built in the last years. Some members of our Inria Project-Team (Munnier, Scheid and Takahashi) developed a collaboration with members of the automatic control laboratory of Nancy CRAN (Daafouz, Jungers) in order 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 carry 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 ([74], [85]). However, in practice the admissible deformations of the ball are limited since they are realized using piezo-electric actuators. In the future, we want to take these constraints into account 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 an 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

- Sphinx was evaluated in March 2017.
- A new ANR project (QUACO) has been accepted; its coordinator is Thomas Chambrion.

6. New Software and Platforms

6.1. 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

6.2. GPELab

Gross-Pitaevskii equations Matlab toolbox
KEYWORDS: 3D - Quantum chemistry - 2D

FUNCTIONAL DESCRIPTION: GPELab is a Matlab toolbox developed to help physicists for computing 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/

7. New Results

7.1. Control and stabilization of heterogeneous systems

7.1.1. Analysis of heterogeneous systems

Participants: Jean-François Scheid, Takéo Takahashi.

In [12], we consider a single disk moving under the influence of a 2D viscous fluid and study the asymptotic as the size of the solid tends to zero. If the density of the solid is independent of the size, the energy equality is not sufficient to obtain a uniform estimate for the solid velocity. This is 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.

In [10], we propose a new model for the motion of a viscous incompressible fluid. More precisely, we consider the Navier-Stokes system with a boundary condition governed by the Coulomb friction law. With this boundary condition, the fluid can slip on the boundary if the tangential component of the stress tensor is too large. We prove the existence and uniqueness of a weak solution in the two-dimensional problem and the existence of at least one solution in the three-dimensional case. In [9], we consider this model with a rigid body. We prove that there exists a weak solution for the corresponding system.

In [13], we study 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's law. We prove the existence and uniqueness of global in time strong solutions. The main novelty is that we include the case of non homogeneous boundary conditions.

In [31], we study the shape differentiability of the free-boundary 1-dimensional simplified model for a fluid-elasticity system. The full characterization of the associated material derivatives is given and the shape derivative of an energy functional has been obtained.

7.1.2. Control of heterogeneous systems

Participants: Thomas Chambrion, Alessandro Duca, Takéo Takahashi.

In [11], we consider the swimming into a stationary Navier-Stokes fluid. The swimmer is a rigid body $\mathcal{S} \subset \mathbb{R}^3$ immersed in an infinitely extended fluid. We are interested in self-propelled motions of $\mathcal{S}$ in the steady state regime of the rigid body-fluid system, assuming that the mechanism used by the body to reach such a motion is modeled through a distribution of velocities on the boundary. We show that this can be solved as a control problem.

In [16] we prove that the Kuramoto-Sivashinsky equation is locally controllable in 1D and in 2D with one boundary control. His method consists in combining several general results in order to reduce the null-controllability of this nonlinear parabolic equation to the exact controllability of a linear beam or plate system. This improves known results on the controllability of Kuramoto-Sivashinsky equation and gives a general strategy to handle the null-controllability of nonlinear parabolic systems.

The paper [21] is the result of a long term analysis about the restrictions to the controllability of bilinear systems induced by the regularity of the propagators for the bilinear Schrödinger equation. This paper comes along with its companion paper [20] which gives a detailed proof of the celebrated Ball-Marsden-Slemrod obstruction to exact controllability for bilinear systems with L^1 controls.

The paper [23] is concerned with the one dimensional bilinear Schrödinger equation in a bounded domain. In this article, we have given the first available upper bound estimates of the time needed to steer exactly the infinite square potential well from its first eigenstate to the second one.

In [22], we present an embedded automatic strategy for the control of a low consumption vehicle equipped with an “on/off” engine. The proposed strategy has been successfully implemented on the Vir'Volt prototype in official competition (European Shell Eco Marathon).

7.1.3. Stabilization of heterogeneous systems

Participants: David Dos Santos Ferreira, Takéo Takahashi, Julie Valein, Jean-Claude Vivalda.

In [8], we find, thanks to a a semiclassical approach, L^p estimates for the resolvants of the damped wave operator given on compact manifolds whose dimension is greater than 2.

In [7], we study the feedback stabilization of a system composed by an incompressible viscous fluid and a deformable structure located at the boundary of the fluid domain. We stabilize the position and the velocity of the structure and the velocity of the fluid around a stationary state by means of a Dirichlet control, localized on the exterior boundary of the fluid domain and with values in a finite dimensional space.

In [19], we study the nonlinear Korteweg-de Vries equation with boundary time-delay feedback. Under appropriate assumption on the coefficients of the feedbacks, we first prove that this nonlinear infinite dimensional system is well-posed for small initial data. The main results of our study are two theorems stating the exponential stability of the nonlinear time delay system, using two different methods: a Lyapunov functional approach and an observability inequality approach.

In [14], we generalize a formula, due to E. Sontag *et al.*, giving explicitly a continuous stabilizing feedback for systems affine in the control; more specifically for a large class of systems which depend quadratically on the control, an explicit formula for a stabilizing feedback law is given.

7.2. Inverse problems for heterogeneous systems

7.2.1. Reconstruction of coefficients and initial conditions

Participants: Karim Ramdani, Julie Valein, Jean-Claude Vivalda.

In [79], we proposed an algorithm for estimating from partial measurements the population for a linear age-structured population diffusion model. In this work, the physical parameters of the model were assumed to be known. In [29], we investigate the inverse problem of simultaneously estimating the population and the spatial diffusion coefficient for an age-structured population model. The measurement used is the time evolution of the population on a subdomain in space and age. The proposed method is based on the generalization to the infinite dimensional setting of an adaptive observer originally proposed for finite dimensional systems.

In [18], we show that, generically, a (finite dimensional) sampled system is observable provided that the number of outputs is at least equal to the number of inputs plus 2. This work complements some previous works on the subject.

7.2.2. Geometrical inverse problems

Participants: Alexandre Munnier, Karim Ramdani, Takéo Takahashi.

In [75], we proposed an explicit reconstruction formula for a two-dimensional cavity inverse problem. The proposed method was limited to the case of a single cavity due to the use of conformal mappings. In [28], we consider the case of a finite number of cavities and aim to recover the location and the shape of the cavities from the knowledge of the Dirichlet-to-Neumann (DtN) map of the problem. The proposed reconstruction method is non iterative and uses two main ingredients. First, the authors show how to compute so-called generalized Pólia-Szegö tensors (GPST) of the cavities from the DtN of the cavities. Secondly, the authors shows that the obtained shape from GPST inverse problem can be transformed into a shape from moments problem, for some particular configurations. However, numerical results suggest that the reconstruction method is efficient for arbitrary geometries.

In [15], we consider the geometrical inverse problem consisting in recovering an unknown obstacle in a viscous incompressible fluid by measurements of the Cauchy force on the exterior boundary. We deal with the case where the fluid equations are the nonstationary Stokes system and using the enclosure method, we can recover the convex hull of the obstacle and the distance from a point to the obstacle. With the same method, we can obtain the same result in the case of a linear fluid-structure system composed by a rigid body and a viscous incompressible fluid.

7.3. Numerical analysis and simulation of heterogeneous systems

Participants: Xavier Antoine, Qinglin Tang.

In [1], we propose a simple accelerated pseudo-spectral algorithm to compute the stationary states of the Gross-Piteavskii Equation (GPE) with possibly multiple components. The method is based on the adaptation of new optimization algorithms under constraints coming from mathematical imaging to the imaginary time (gradient-like) method for the GPE arising in Bose-Einstein Condensation.

In [3] we propose original efficient preconditioned conjugate gradient methods coming from molecular physics to the GPE for spectrally computing the stationary states of the GPE. The method allows a gain of a factor 100 for 3D problems with extremely large nonlinearities and fast rotations. The HPC solver is being developed.

In [17], we develop new robust and efficient algorithms for computing the dynamics of 2-components GPEs with dipolar interaction. The main particularity of the method is that high accuracy is obtained by a new FFT based evaluation of nonlocal kernels applied to the nonlinear part of the operator.

In [4], we propose an asymptotic mathematical analysis of domain decomposition techniques for solving the 1D nonlinear Schrödinger equation and GPE. The analysis uses advanced techniques related to fractional microlocal analysis for PDEs. Simulations confirm the mathematical analysis.

In [2], we extend, by some very technical mathematical analysis, approaches for the results stated in [4]. Again, numerical simulations validate the theoretical analysis.

In [5], we develop and implement in parallel simple new solvers for computing the dynamics of solutions to the Dirac equation arising in quantum physics. Numerical examples are developed to analyze the capacity of these algorithms for a parallel implementation.

In [6], we introduce the concept of Absorbing Boundary Conditions and Perfectly Matched Layers for the dynamics of nonlinear problems related to classical and relativistic quantum wave problems (Wave equation, Schrödinger equation, Dirac eqution). In particular, we show application examples and detail the methods so that they can be implemented by researchers coming for quantum physics.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Grants with Industry

From February 2018, T. Chambrion will be the advisor of Ayoub Lasri for a PhD thesis (CIFRE label pending) on the stabilization of the Mosel river funded by *Voies Navigables de France*. This thesis is part of an international cooperation with BAW (the German counterpart of VNF, based in Karlsruhe) and Universität Stuttgart started in November 2017.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. ANR

- **Project Acronym :** iproblems
  Project Title : Inverse Problems
  Coordinator : David Dos Santos Ferreira
  Duration : 48 months (2013-2017)
  Partner: Institut Élie Cartan de Lorraine
  URL: http://www.agence-nationale-recherche.fr/Projet-ANR-13-JS01-0006
- **Project Acronym :** IFSMACS
  Project Title : Fluid-Structure Interaction: Modeling, Analysis, Control and Simulation
  Coordinator: Takéo Takahashi
  Participants: Julien Lequeurre, Alexandre Munnier, Jean-François Scheid, Takéo Takahashi
  Duration : 48 months (starting on October 1st, 2016)
  Other partners: Institut de Mathématiques de Bordeaux, Inria Paris, Institut de Mathématiques de Toulouse
  Abstract: The aim of this project is to analyze systems composed by structures immersed in a fluid. Studies of such systems can be motivated by many applications (motion of the blood in veins, fish locomotion, design of submarines, etc.) but also by the corresponding challenging mathematical problems. Among the important difficulties inherent to these systems, one can quote nonlinearity, coupling, free-boundaries. Our objectives include asymptotic analyses of FSIS, the study of controllability and stabilizability of FSIS, the understanding of locomotion of self-propelled structures and the analyze and development of numerical tools to simulate fluid-structure system.
  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)
  Other partners: EADS (France Innovation Works Dep.), NUCLETUDES
  URL: http://www-sop.inria.fr/nachos/projects/tecser/index.php/Main/HomePage
- **Project Acronym:** BoND
  Project Title: Boundaries, Numerics and Dispersion.
  Coordinator: Sylvie Benzoni (Institut Camille Jordan, Lyon, France)
  Participant: Xavier Antoine
  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)
  Participant: Xavier antoine
  Duration: 48 months (plus an extension of 12 months, until November 2017)
  Other partners: Laboratoire de Mathématiques Raphaël Salem, (Université de Rouen); Laboratoire Jacques-Louis Lions (Université Pierre et Marie Curie); Centre de Mathématiques Appliquées (Ecole Polytechnique); Centre d'Enseignement et de Recherche en Mathématiques et Calcul Scientifique (École des Ponts ParisTech); Loria; Laboratoire Paul Painlevé (Université Lille 1) et Inria-Lille Nord-Europe; Institut de Mathématiques et de Modélisation de Montpellier (Université Montpellier 2)
  URL: http://becasim.math.cnrs.fr

- **Project Acronym:** QUACO
  Project title: use of geometrical tools for the control of quantum system and application to MRI.
  Coordinator: Thomas Chambrion
  Duration: 48 months (starting January 1st 2018).
- **Project acronym:** ISDEEC
  Project title: Interaction entre Systèmes Dynamiques, Equations d'Evolution et Contrôle
  Coordinator: Romain Joly
  Participant: Julie Valein
  Other partners: Institut Fourier, Grenoble; Département de Mathématiques d'Orsay
  Duration: 36 months (2017-2020)
  URL: http://isdeec.math.cnrs.fr/

9.1.2. CNRS

Thomas Chambrion is the coordinator of the Research Project from CNRS Inphynity "DISQUO" (5300 euros, 2017).

9.2. International Initiatives

9.2.1. Participation in Other International Programs

D. Dos Santos Ferreira and J.-F. Scheid are members of the PHC Utique program ...

Program: PHC Utique
Project title: Équations aux Dérivées Partielles Déterministes et Stochastiques
Duration: January 2017-January 2020
Other partners: Laboratoire de Modélisation De´terministe et Ale´atoire (LAMDA), École Supérieure des Sciences et de la Technologie de Hammam Sousse (ESSTHS), Université de Sousse, Tunisie.
Abstract: The main objective of this project is to study some systems of Ordinary Differential Equations (ODE) and Partial Differential Equations (PDE) in a deterministic and stochastic frameworks with analytical, numerical, probabilistic or statistical methods. A typical system considered in this project is the modeling and the numerical simulations of the myocardial infarction (heart attack). This phenomenon is studied as a fluid/structure interaction type process between the blood, the cholesterol deposit along the walls of an artery and the rupture of the atherosclerotic plaque formed by the cholesterol.

This is a project for a French-Tunisian collaboration and it involved a PhD thesis co-advised by J.-F. Scheid.

J. Valein is member of the project ICoPS:

Program: MATH-AmSud
Project acronym: ICoPS
Project title: Inverse and control problems for physical systems
Duration: 01/2017-12/2018
Coordinators: Alberto Mercado (Valparaíso, Chile), Emmanuelle Crépeau (Versailles), Daniel Alfaro (Rio de Janeiro, Brasil), Ivonne Rivas (Colombia)
Other partners: Centre Automatique et Systèmes (École des Mines de Paris), LAAS (Toulouse), Instituto de Matemática, Estadística e Física (Universidade Federal do Rio Grande do Sul, Brasil), Departamento de Matemáticas y Estadística, (Universidad Icesi, Pance, Cali, Colombia)
Abstract: We propose to study well-posedness, control properties, and coefficient inverse problems for partial differential equations appearing in models for several phenomena. We intend to study the inverse problems of recovering some coefficients in the previously mentioned equations, and also in nonlinear dispersive waves on trees, which appears for instance in model for the cardiovascular system. We intend to study numerical approximations, using numerical schemes like Galerkin, colocation, finite difference, among others. Finally, this proposal includes the determination of the reachable states in a control problem of KdV equation.

9.3. International Research Visitors

J.-F. Scheid has been visitor of the l'ESSTHS (Hammam-Sousse, Tunisia) for two weeks (work related to the thesis of Imen JBILI) and course on numerical methods for the Navier-Stokes equations).

9.3.1. Visits of International Scientists

Sorin Micu (University of Craiova) was an invited professor (University of Lorraine) from 12/01/2017 to 12/02/2017.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. Member of the Organizing Committees

K. Ramdani was member of the Organizing Committee of the Conference "Accès ouvert : rêve ou réalité ?" (CIRM, October 2017) organized by the RNBM (Réseau National des Bibliothèques de Mathématiques). During this conference, two days were more especially scientists-oriented and devoted to new models of publication, and more especially open access journals (for more details, see: http://www.rnbm.org/cirm-2017).

10.1.1.2. General chair, Scientific chair

T. Takahashi co-organized a conference, in the framework of the ANR's project IFSMACS, at the Institut de Mathématiques de Bordeaux from the 2nd to the 5th of October 2017 (see https://indico.math.cnrs.fr/event/1367/).

10.1.2. Journal

10.1.2.1. Member of the Editorial Boards

J.-C. Vivalda is a member of the editorial board of the "Journal of Dynamical and Control Systems". David Dos Santos Ferreira is member of the editorial board of "Mathematical Control and Related Fields".

10.1.2.2. Reviewer - Reviewing Activities

J.-F. Scheid is reviewer for the "Applied Mathematics and Optimization" journal.

J.-C. Vivalda is reviewer for the "Mathematical reviews".

10.1.3. Invited Talks

- T. Chambrion has been invited to the "Recife Workshop on Control and Stabilization of PDEs" held from 13 to 17 February 2017 in Recife (Brasil). See https://sites.google.com/site/recontrolpde/.
- T. Chambrion has been invited to the seminar of Université de Nice (analysis) in November 2017 and Strasbourg (December 2017).
- T. Takahashi was an invited speaker at the conference CDPS 2017 in Bordeaux (see https://indico.math.cnrs.fr/event/1363/).

10.1.4. Leadership within the Scientific Community

T. Chambrion has been a co-animator (with F. Di Meglio) of the GT EDP in GDR MACS until the redesign of the working groups in November 2017.

D. Dos Santos Ferreira is one of the coordinators of the GDR "Analyse des EDP".

10.1.5. Research Administration

- Karim Ramdani was deputy delegate for scientific affairs of the Inria Nancy research center until August 31, 2017.
- Karim Ramdani is member of the board of the RNBM (Réseau National des Bibliothèques de Mathématiques) and is in charge with Benoît Kloeckner of Open Access issues.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

With the exception of K. Ramdani, T. Takahashi and J.-C. Vivalda, SPHINX members have teaching obligations at "Universite´ de Lorraine" and are teaching at least 192 hours each year. They teach mathematics at different level (Licence, Master, Engineering school). Many of them have pedagogical responsibilities.

10.2.2. Supervision

PhD in progress: Mohamed ID SAID, Embedded automatic control with limited computational resources, from October 2017, supervisors: T. Chambrion and G. Millerioux;

PhD in progress: Meriem BOUGUEZZI, Reaction-diffusion system for the modeling of a corrosion phenomena, from november 2017, J.-F. Scheid (co-supervisor);

PhD in progress: Imem JBIL, Myocardial infarction as a fluid-structure system : modeling and simulations, from mars 2017, J.-F. Scheid (co-supervisor);

PhD in progress: Imene DJEBOUR, Control and inverse problems on fluid-structure interaction systems, from November 2017, supervisor : Takahashi

PhD in progress: Benjamin Obando, Mathematical study of the dynamics of heterogeneous granular flows, from August 2015, supervisors : Takahashi and San Martín (Universidad de Chile)

10.2.3. Juries

David Dos Santos Ferreira reviewed the application of Joonas Ilmavirta for position of “docent” at Helsinki University. He was also a member of the HDR (Accreditation to Supervise Research) thesis jury of Yavar Kian (defended in November 2017).

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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

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Team TONUS

Creation of the Team: 2012 January 01

Keywords:

Computer Science and Digital Science:

A6. - Modeling, simulation and control
A6.1. - Mathematical Modeling
A6.1.1. - Continuous Modeling (PDE, ODE)
A6.1.4. - Multiscale modeling
A6.1.5. - Multiphysics modeling
A6.2. - Scientific Computing, Numerical Analysis & Optimization
A6.2.1. - Numerical analysis of PDE and ODE
A6.2.7. - High performance computing
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A7.1. - Algorithms
A8.9. - Performance evaluation

Other Research Topics and Application Domains:

B1.1.10. - Mathematical biology
B4.2.2. - Fusion
B5.2.3. - Aviation
B6.1.1. - Software engineering

1. Personnel

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Sever Hirstoaga [Inria, Researcher]

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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 modelling 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, gyrokinetic and fluid simulations of tokamak 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 have strong relations with the CEA-IRFM team and participate in the development of their gyrokinetic simulation software GYSELA. We are involved in two Inria Project Labs, respectively devoted to tokamak mathematical modelling and high performance computing. The numerical tools developed from plasma physics can also be applied in other contexts. For instance, we collaborate with a small company in Strasbourg specialized in numerical software for applied electromagnetism. We also study kinetic acoustic models with the CEREMA and multiphase flows with EDF.

Finally, our topics 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 relativistic particles into account, which leads to consider the relativistic Vlasov equation, even if in general, tokamak plasmas are supposed to be non-relativistic. The distribution function of particles depends on seven variables (three for space, three for the 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 a prohibitive amount of calculations. It is then necessary to develop reduced models for large magnetic fields 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.

On the boundary of the plasma, the collisions can no more be neglected. Fluid models, such as the MagnetoHydroDynamics (MHD) become again relevant. For the good operation of the tokamak, it is necessary to control MHD instabilities that arise at the plasma boundary. Computing these instabilities requires special implicit numerical discretizations with excellent long time behavior.

In addition to theoretical modelling tools, it is necessary to develop numerical schemes adapted to kinetic, gyrokinetic and fluid 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 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. Implementing Two-Scale Numerical Methods (for instance by Frénod et al. [23]) is 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) that 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. [22].

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 long-standing 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 [24].

More recently, we have started to apply the Semi-Lagrangian methods to more general kinetic equations. Indeed, most of the conservation laws of physics can be represented by a kinetic model with a small set of velocities and relaxation source terms [7]. Compressible fluids or MHD equations have such representations. Semi-Lagrangian methods then become a very appealing and efficient approach for solving these equations.

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 this approach 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 long-standing experience in PIC methods and we started implementing them in Selalib. An important aspect is to adapt the method to new multicore computers. See the work by Crestetto and Helluy [21].

3.2. Fluid and 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.

But 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).

In the fluid or reduced-kinetic regions, the approximation of the distribution function could require fewer data while still achieving a good representation, even in the collisionless regime.

Therefore, a fluid or 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 the solution of a first order hyperbolic system.

Another way to reduce the model is to try to find an abstract kinetic representation with an as small as possible set of kinetic velocities. The kinetic approach has then only a mathematical meaning. It allows solving very efficiently many equations of physics [13].

3.2.1. 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], [20], [26], [25].

3.2.2. Matrix-free Implicit schemes

In tokamaks, the reduced model generally involves many time scales. Among these time scales, many of then, associated to the fastest waves, are not relevant. In order to filter them out, it is necessary to adopt implicit solvers in time. When the reduced model is based on a kinetic interpretation, it is possible to construct implicit schemes that do not impose solving costly linear systems. In addition the resulting solver is stable even at very high CFL number [13].

3.3. Electromagnetic solvers

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 one 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 [18] (and the references therein).

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 50'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 antennas, 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 modelling 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 (PhD of Pierre Gerhard). The objective is to investigate the model reduction and to implement the resulting acoustic model in our DG solver.
- In september 2017, we started a collaboration with EDF Chatou (PhD of Lucie Quibel) on the modelling of multiphase fluids with complex equations of state. The goal is to simulate the high temperature liquid-vapor flow occurring in a nuclear plant. Among others, we will apply our recent kinetic method for designing efficient implicit schemes for this kind of flows.

5. Highlights of the Year

5.1. Highlights of the Year

We have developed [7] a new numerical method for solving any hyperbolic system of conservation laws (and among them the reduced plasma models). The method is based on a vectorial kinetic representation of the equations, an efficient transport solver (suc as DG or Semi-Lagrangian) and palindromic time integration. The resulting scheme is unconditionally stable, matrix-free and high order. We applied it successfully to the simulation of Rayleigh-Taylor instabilities and we are extending it to the simulation of MHD instabilities.

6. New Software and Platforms

6.1. CLAC

Conservation Laws Approximation on many Cores

SCIENTIFIC DESCRIPTION: It is clear now that 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). When designing new algorithms, it is important to adapt them to this kind of architecture. Our philosophy will be to program our algorithms in such a way that they can be run efficiently on this kind of computers. Practically, we will use the MPI library for managing the coarse grain parallelism, while the OpenCL library will 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.

Because of the envisaged applications of CLAC, which may be either academic or commercial, it is necessary to conceive a modular framework. The heart 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. In this way, it is possible to isolate parts that should be protected for trade secret reasons.
FUNCTIONAL DESCRIPTION: CLAC is a generic Discontinuous Galerkin solver, written in C/C++, based on the OpenCL and MPI frameworks.

- Partner: AxesSim
- Contact: Philippe Helluy
- URL: http://clac.gforge.inria.fr/

6.2. Selalib

SEmi-LAgrangian LIBrary
KEYWORDS: Plasma physics - Semilagrangian method - 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 Insitute - Garching - Université de Strasbourg
- Contact: Philippe Helluy
- URL: http://selalib.gforge.inria.fr/

6.3. SCHNAPS

Solver for Conservative Hyperbolic Nonlinear Applications for PlasmaS
KEYWORDS: Discontinuous Galerkin - StarPU - Kinetic scheme
FUNCTIONAL DESCRIPTION: Generic systems of conservation laws. Specific models: fluids, Maxwell, Vlasov, acoustics (with kinetic representation). Multitasking with StarPU. Explicit solvers (RK2, RK3, RK4): accelerated with OpenCL Implicit solvers: through kinetic representations and palindromic time integration.

- Contact: Philippe Helluy
- URL: http://schnaps.gforge.inria.fr/

7. New Results

7.1. Palindromic methods

7.1.1. Palindromic discontinuous Galerkin method in 2D and 3D

Participants: David Coulette, Florence Drui, Emmanuel Franck, Philippe Helluy, Laurent Navoret.

In the previous year (see [7]) we have proposed a method to solve hyperbolic systems like the Euler equations with an unconditionally stable high-order method. This method is based on a kinetic representation of the hyperbolic system. The kinetic equations are solved with an upwind DG method. It requires no matrix storage. High order is obtained through palindromic composition methods. The concept has been test in 1D. During this year we extend the method to 2D and 3D and applied it to fluid mechanics. Currently we are working on improving this method on realistic cases for MHD instabilities. The objective is to compare the results with the European code JOREK.

We are also working on methods for applying boundary conditions in a stable way with the palindromic method (postdoc of Florence Drui).

7.1.2. Kinetic model for palindromic methods

Participants: David Coulette, Emmanuel Franck, Laurent Navoret.

One of the most important drawbacks of the Palindromic method is the numerical dispersion associated to the high-order time scheme. To limit this problem we propose to replace the DG method by a semi-Lagrangian method and design new kinetic representations which are more accurate. We also studied the stability of these news models. The first results were good and currently we are working on the 2D extension and the coupling with limiter technics.

7.1.3. Finite element relaxation methods for fluid models

Participants: David Coulette, Emmanuel Franck.

In parallel to our work on the Palindromic method based on a kinetic relaxation model, we studied in [17] a variant based on the Xin-Jin relaxation model. Coupled with a finite element method we obtain an implicit solver for Euler equations where we invert only Laplacians and mass matrices. The first results show that the method is more efficient in CPU costs and memory. The finite elements used are the same as in JOREK.

7.2. MHD problems

Participant: Emmanuel Franck.

7.2.1. Compatible Implicit finite element for linear MHD

In this work we consider a linear MHD problem. The aim is to design an implicit method able to preserve the energy equation and the divergence free constraints in realistic Tokamak geometry. The first idea is to use a splitting scheme between the wave and convection parts coupled with an implicit scheme for each subsystem. In order to discretize each sub-system we use compatible B-Splines FE method wich allows us to preserve the invariants and to use a reduction of the implicit problem to be inverted. The idea was improved on simple geometries. We are currently extending the method on realistic geometries.

7.2.2. Splitting and relaxation for JOREK code

The Jorek code is the main European code for the simulation of Tokamak instabilities. The inversion of the full matrix is based on Block Jacobi preconditioning which is not efficient in some cases and very greedy in memory. We are investigating a new splitting scheme similar to the one used in works on compatible Finite Elements. We have also just begun to investigate the relaxation method used in the Palindromic scheme to solve the reduced MHD model of JOREK.

7.3. Finite Volume approximations of the Euler system with variable congestion

Participants: Pierre Degond, Piotr Minakowski, Laurent Navoret, Ewelina Zatorska.

We are interested in the numerical simulations of the Euler system with variable congestion encoded by a singular pressure. This model describes for instance the macroscopic motion of a crowd with individual congestion preferences. In [3] we propose an asymptotic preserving (AP) scheme based on a conservative formulation of the system in terms of density, momentum and density fraction. A second order accuracy version of the scheme is also presented. We validate the scheme on one-dimensional test cases and compare it with a scheme developed in a previous work and extended here to higher order accuracy. We finally carry out two-dimensional numerical simulations and show that the model exhibits typical crowd dynamics.

7.4. Numerical scheme for sheath equilibria

Participants: Mehdi Badsi, Michel Mehrenberger, Laurent Navoret.

We are interested in developing a numerical method for capturing stationary sheaths that a plasma forms in contact with a metallic wall. This work is based on a bi-species (ion/electron) Vlasov-Ampère model proposed in [19]. The main question addressed in this work is to know if classical numerical schemes can preserve stationary solutions with boundary conditions, since these solutions are not a priori conserved at the discrete level. In the context of high-order semi-Lagrangian method, due to their large stencil, interpolation near the boundary of the domain also requires a specific treatment. Moreover, for preventing instabilities from developing in large time, the proposed method guaranties that the discrete Gauss equation is satisfied in time.

7.5. Recurrence phenomenon for finite element grid based Vlasov solver

Participants: Michel Mehrenberger, Laurent Navoret, Thi Nhung Pham.

When using a grid based solver (finite element/DG scheme, discontinuous Galerkin semi-Lagrangian scheme) and spatial periodic boundary conditions, the simulations of the Vlasov-Poisson system exhibit numerical reappearance of initial perturbations at some time called recurrence time. This time depends on the numerical parameters (degree and mesh size of the finite element mesh). With a given number of degrees of freedom, considering a large degree approximation makes the phenomenon appear earlier in the simulation and thus makes this choice less attractive. In our work [9], we highlight that the time and the intensity of the recurrence are related to the quadrature rules used for computing the charge density. In particular, quadratures that are exact on trigonometric polynomials weaken the recurrence effect.

7.6. PICSL

Participants: Yann Barsamian, Joackim Bernier, Sever Hirstoaga, Michel Mehrenberger.

7.6.1. Particle in Cell and Semi-Lagrangian schemes for two species plasma simulations

Thanks to a classical first order dispersion analysis, we are able to check the validity of $1D\times1D$ two species Vlasov-Poisson simulations; the extension to second order is performed and shown to be relevant for explaining further details. In order to validate multidimensional effects, we propose in [14] a $2D \times 2D$ single species test problem that has true 2D effects coming from the sole second order dispersion analysis. Finally, we perform, in the same code, full $2D\times2D$ nonlinear two species simulations with mass ratio and consider the mixing of semi-Lagrangian and Particle-in-Cell methods. This work has been initiated at CEMRACS 2016.

7.7. TARGET

Participants: Nicolas Bouzat, Guillaume Latu, Camilla Bressan, Michel Mehrenberger, Virginie Grandgirard.

7.7.1. TArgeting Realistic GEometry in Tokamak code gysela

The framework of the work in [16] is the Semi-Lagrangian setting for solving the gyrokinetic Vlasov equation and the Gysela code. A new variant for the interpolation method is proposed that can handle the mesh singularity in the poloidal plane at $r = 0$ (a polar system is used for the moment in Gysela). A non-uniform meshing of the poloidal plane is proposed, instead of a uniform one, in order to save memory and computations. The interpolation method, the gyroaverage operator, and the Poisson solver are revised in order to cope with non-uniform meshes. A mapping that establishes a bijection from polar coordinates to more realistic plasma shapes is used to improve the realism. Convergence studies are provided to establish the validity and robustness of our new approach. This work has been initiated at CEMRACS 2016.

7.8. Field-aligned interpolation for gyrokinetics

Participants: Yaman Güclü, Philippe Helluy, Guillaume Latu, Michel Mehrenberger, Laura Mendoza, Eric Sonnendrücker, Maurizio Ottaviani.

This work is devoted to the study of field-aligned interpolation in semi-Lagrangian codes. This work has been initiated in 2013; this year the article has been accepted [5]. In the context of numerical simulations of magnetic fusion devices, this approach is motivated by the observation that gradients of the solution along the magnetic field lines are typically much smaller than along a perpendicular direction. In toroidal geometry, field-aligned interpolation consists of a 1D interpolation along the field line, combined with 2D interpolations on the poloidal planes (at the intersections with the field line). A theoretical justification of the 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). In the first case, the algorithm is implemented in Selalib (semi-Lagrangian library), and the numerical simulations provide linear growth rates that are in accordance with the linear dispersion analysis. In the second case, the algorithm is implemented in the Gysela code, and the numerical simulations are benchmarked with those employing the standard (not aligned) scheme. Numerical experiments show that field-aligned interpolation leads to considerable memory savings for the same level of accuracy; substantial savings are also expected in reactor-scale simulations.

We are also currently implementing into SCHNAPS a general transport solver for addressing non-conforming patches in complex geometries. The objective is to be able to design meshes that are able to deal with magnetic aligned geometries. The resulting scheme will be used for solving kinetic equations, of course. But it can also be the building block of a palindromic method applied on curved and non-conforming meshes.

7.9. InKS

Participants: Olivier Aumage, Julien Bigot, Ksander Ejjaaouani, Michel Mehrenberger.

7.9.1. A programming model to decouple performance from semantics in simulation codes

Existing programming models lead to a tight interleaving of semantics and computer optimization concerns in high-performance simulation codes. With the increasing complexity and heterogeneity of supercomputers this requires scientists to become experts in both the simulated domain and the optimization process and makes the code difficult to maintain and port to new architectures. The report in [12] proposes InKS, a programming model that aims to improve the situation by decoupling semantics and optimizations in code so as to ease the collaboration between domain scientists and experts in high-performance optimizations. We define the InKS language that enables developers to describe the semantics of a simulation code with no concern for performance. We describe the implementation of a compiler able to automatically execute this code without making any explicit execution choice. We also describe a method to manually specify these choices to reach high-performance. Our preliminary evaluation on a 3D heat equation solver demonstrates the feasibility of the automatic approach as well as the ability to specify complex optimizations while not altering the semantic part. It shows promising performance where two distinct specifications of optimization choices in InKS offer similar performance as existing hand-tailored versions of the solver.

7.10. Performance of Particle-in-Cell methods

Participants: Yann Barsamian, Sever Hirstoaga, Eric Violard.

In a two-dimensional framework, in [6] we optimized a Particle-in-Cell (PIC) code by analyzing different data structures for the particles and for the grid fields with the aim of improving the cache reuse and by using the vectorization from the compiler. We also parallelized the code with OpenMP/MPI and satisfactory strong and weak scaling up to 8192 cores were obtained on the supercomputer CURIE.
Currently [15] we are extending and improving this work to a three-dimensional electrostatic PIC code.

7.11. Comparison of multiscale PIC methods

Participants: Nicolas Crouseilles, Sever Hirstoaga, Xiaofei Zhao.

In [2] we study different types of multiscale methods to numerically study the long-time Vlasov–Poisson equation with a strong magnetic field. The multiscale methods are an asymptotic preserving Runge–Kutta scheme, an exponential time differencing scheme, the stroboscopic averaging method and a uniformly accurate two-scale formulation. Extensive numerical experiments are conducted to investigate and compare the accuracy, efficiency, and long-time behavior of all the methods. The methods with the best performance under different parameter regimes are identified.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Grants with Industry

We are involved in the PhD direction of Lucie Quibel in collaboration with EDF Chatou (CIFRE support). The objective is to design new Equations Of States (EOS) for the simulation of multiphase flows. The EOS cannot be chosen arbitrarily if one wants to ensure the stability of the fluid model. We are also interested to apply our palindromic method for computing low-Mach liquid-vapor flows.

9. Partnerships and Cooperations

9.1. 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.

9.2. National Initiatives

9.2.1. Contracts with Industry

We are involved in a common project with the company AxesSim in Strasbourg. The objective is to help to the development of a commercial software for 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. A CIFRE PhD has started in AxesSim on the same kinds of subjects in March 2015 (Bruno Weber). The new project is devoted to the use of runtime system in order to optimize DG solvers applied to electromagnetism [10]. The resulting software will be applied to the numerical simulation of connected devices for clothes or medicine. The project is supported by the "Banque Publique d'Investissement" (BPI) and coordinated by the Thales company.

9.2.2. ANR

ANR project PEPPSI (models for edge plasma physic in Tokamak) in *Programme Blanc* SIMI 9, started in 2013, ended this year.
Participants: David Coulette, Giovanni Manfredi [coordinator], Sever Hirstoaga.

9.2.3. IPL FRATRES

The TONUS project belongs to the IPL FRATRES (models and numerical methods for Tokamak).
Funded by the IPL, Xiaofei Zhao was a post-doctoral fellow until September 2017, under the joint supervision of Nicolas Crouseilles (team IPSO, Inria Rennes) and Sever Hirstoaga.

9.2.4. 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.

9.2.5. HPC resources

- GENCI project *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 Hirstoaga, Guillaume Latu, Michel Mehrenberger, Thi Nhung Pham, Christophe Steiner, Yann Barsamian.
- GENCI project *Simulations 3D de plasmas deux espèces avec des méthodes particulaires et semi-lagrangiennes*: 400 000 scalar computing hours accepted in October 2017 on supercomputer OCCIGEN. Coordinator: Sever Hirstoaga
  Participants: Yann Barsamian, Sever Hirstoaga, Michel Mehrenberger.
- PRACE project *SME HPC Adoption Programme in Europe: full simulation of an electromagnetic wave inside and ouside a fully modeled human body*: 40 000 GPU computing hours accepted in October 2017 on supercomputer Piz Daint. Coordinator: Bruno Weber
  Participants: Philippe Helluy, Bruno Weber.

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

9.3.1.1. 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 Hirstoaga, Michel Mehrenberger.
- Eurofusion Enabling Research Project ER15-IPP05 (1/2015-12/2017) "Global non-linear MHD modelling 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.

9.4. International Initiatives

9.4.1. Participation in Other International Programs

Participants: David Coulette, Conrad Hillairet, 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.

9.5. International Research Visitors

9.5.1. Visits of International Scientists

Christian Klingenberg from Würzburg university was invited several times in 2017, by Philippe Helluy.

Roberto Ferretti was invited one month in 2017 at IRMA, by Michel Mehrenberger, for working on the stability of semi-Lagrangian schemes.

9.5.2. Visits to International Teams

9.5.2.1. Research Stays Abroad

Philippe Helluy, Emmanuel Franck and David Coulette visited Christian Klingenberg at Würzburg university.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. Member of the Organizing Committees

Philippe Helluy is member of the French candidature committee for the organization of the International Congress of Mathematics in 2022 in Paris and Strasbourg https://www.icm2022-paris.com/.

10.1.2. Journal

10.1.2.1. Member of the Editorial Boards

Philippe Helluy is in the editorial board of

- International Journal of Finite Volume
- Computational and Applied Mathematics

10.1.2.2. Reviewer - Reviewing Activities

Emmanuel Franck was a reviewer for

- Communication in computation physics
- Computer Methods in Applied Mechanics and Engineering
- Journal of Computational Physics

Philippe Helluy has done reviews for

- Numerical Methods for Partial Differential Equations
- Journal of Computational Physics
- Computers and Fluids
- M2AN
- Esaim Proceedings and reviews

Sever Hirstoaga was a reviewer for

- Journal of Computational and Applied Mathematics (2 papers)
- Journal of Approximation Theory
- SIAM Journal on Optimization
- Multiscale Modeling and Simulation: A SIAM Interdisciplinary Journal
- MathSciNet/Mathematical Reviews

Michel Mehrenberger participates in reviewing for

SIAM Journal on Scientific Computing

Mathematical Methods in the Applied Sciences

Evolution Equations and Control Theory

Journal of Computational Physics

International Conference on Physics, Mathematics and Statistics 2018

Applied Mathematics and Computation

Computer Physics Communications

Laurent Navoret was a reviewer for

Kinetic and Related Models

10.1.3. Invited Talks

Emmanuel Franck was invited at

Enumath conference, Bergen, September 2017.

the Workshop JOREK, Prague, March 2017.

the IPL Fratres Meeting, Rennes, November 2017.

Philippe Helluy was invited at

NUMKIN 2017, Garching November 2017

Fast high order DG methods for future architectures Heidelberg July 2017

Workshop - "Modeling and Numerical Methods for Hot Plasmas III": 12-13 octobre 2017 Bordeaux

Sever Hirstoaga was invited at

the “Séminaire d’analyse numérique”, at IRMAR, Rennes, February 2nd, 2017.

Michel Mehrenberger

gave a talk entitled «About recurrence time for a semi-Lagrangian discontinuous Galerkin Vlasov solver» at Collisionless Boltzmann (Vlasov) Equation and Modeling of Self-Gravitating Systems and Plasmas, CIRM (Marseille), 30 october-3 november 2017.

was invited at the seminar «Analyse Numérique et Calcul Scientifique» of Besançon “Méthodes numériques pour la physique des plasmas”, February 16, 2017.

Larent Navoret was invited at

the Seminar of the Interdisciplinary Center for Scientific Computing, Heidelberg, Germany

10.1.4. Scientific Expertise

Philippe Helluy is in the evaluation committee of the “réseau calcul” of CNRS.

10.1.5. Research Administration

Philippe Helluy

has been elected as the Director of the IRMA mathematics institute (official start in september 2018).

Sever Hirstoaga

was member of the hiring committee for an associate professor position at the ENS Mécanique et des Microtechniques, Besançon.

Michel Mehrenberger

is in the IREM ("Institut de recherche sur l’enseignement des mathématiques") team "Modélisation" for the year 2017-2018, Université de Strasbourg.

is in the committee of the Ecole Doctorale ED269, EDMSII, Université de Strasbourg.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

M1: Philippe Helluy, algorithmes pour les graphes 30 HETD

M2: Philippe Helluy, Contrôle optimal 30 HETD

M2: Philippe Helluy, EDP hyperboliques 30 HETD

L2: Philippe Helluy, Calcul scientifique 64 HETD

Ecole d'ingénieurs: Philippe Helluy, recherche opérationnelle 40 HETD, analyse numérique 40 HETD

Licence: Michel Mehrenberger, Calcul scientifique, 65 h eq. TD, L3, Université de Strasbourg, France.

Licence: Michel Mehrenberger, Optimisation Non-Linéaire, 54h eq. TD, Cours et TD, L3 Maths-Eco, Université de Strasbourg, France

Master: Michel Mehrenberger, Calcul scientifique, 32.5h eq. TD, Cours et TP, M1 CSMI, Université de Strasbourg, France.

Master: Michel Mehrenberger, PIP: certification python, 13h eq. TD, TP, M1 Mathématiques, Université de Strasbourg, France.

Master: Michel Mehrenberger, Calcul scientifique, 22 h eq. TD, TP, M2 Agrégation, Université de Strasbourg, France.

Licence : Laurent Navoret, Nonlinear optimization (18h eq. TD), L3 Maths-Eco, Université de Strasbourg, France.

Master 1: Laurent Navoret, Python (32,5h eq. TD), Université de Strasbourg, France.

Master 2 (Agrégation) : Laurent Navoret, scientific computing (60h eq. TD), Université de Strasbourg, France.

Master 2 (Cell physics) : Laurent Navoret, Basics in maths (24h eq. TD), Université de Strasbourg, France.

Master 2 (Agrégation) : Laurent Navoret, Head of the master, Université de Strasbourg, France.

10.2.2. Supervision

Philippe Helluy has been Habilitation "garant" of Olivier Hurisse (EDF) and Marcela Szopos (IRMA), at université de Strasbourg.

PhD in progress: Lucie Quibel (CIFRE support): in collaboration with EDF Chatou, from October 2017, Advisor: Philippe Helluy.

PhD in progress: Marie Houillon: “Modeling of thin wires in electromagnetic software”, Advisors: Philippe Helluy and Laurent Navoret, from October 2017, Labex Irmia support.

PhD in progress: Bruno Weber(CIFRE support): “Optimization of DG software on GPU in the AxesSim company”. Advisor: Philippe Helluy.

PhD in progress: Maxime Schmitt: “Optimization of scientific software with arbirary mesh refinement”, Advisors: Philippe Helluy and Cédric Bastoul (CAMUS team). Labex Irmia support.

PhD in progress: Ksander Ejjaaouani, "Conception of a programmation model, application to gyrokinetic simulations", from October 2016, Advisors: Michel Mehrenberger, Julien Bigot, Olivier Aumage.

PhD in progress: Nicolas Bouzat, "Conception of a programmation model, application to gyrokinetic simulations", from October 2015, Advisors: Michel Mehrenberger, Jean Roman, Guillaume Latu.

PhD in progress: Pierre Gerhard, "Résolution des modèles cinétiques. Application à l'acoustique du bâtiment", from October 2015, Advisors: Philippe Helluy, Laurent Navoret.

Conrad Hillairet: interrupted thesis at the request of the student.

10.2.3. Juries

Philippe Helluy was member of the following juries

jury of the PhD committee of Tohir Akramov, in astrophysics, université de Strasbourg, 28 September 2017.

jury of the PhD committee of Thomas Altazin, in scientific computing, université de Toulon, 7 September 2017.

jury of the PhD committee of Laura Mendoza, in plasma physics, Max Planck Institut for Plasma Physics, Garching.

jury of the PhD committee of Florence Drui, in multiphase models, Ecole Centrale Paris, 7 July 2017.

Michel Mehrenberger was member of the jury of the PhD committee of Mohammad Akil (Université de Limoges), 6 October 2017.

11. Bibliography

Publications of the year

Articles in International Peer-Reviewed Journal

[1] F. CASAS, N. CROUSEILLES, E. FAOU, M. MEHRENBERGER.*High-order Hamiltonian splitting for Vlasov-Poisson equations*, in "Numerische Mathematik", 2017, vol. 135, n^{o} 3, p. 769-801, https://arxiv.org/abs/1510.01841 [*DOI :* 10.1007/S00211-016-0816-Z], https://hal.inria.fr/hal-01206164.

[2] N. CROUSEILLES, S. A. HIRSTOAGA, X. ZHAO.*Multiscale Particle-in-Cell methods and comparisons for the long-time two-dimensional Vlasov-Poisson equation with strong magnetic field*, in "Computer Physics Communications", October 2017, vol. 222, p. 136-151, https://hal.archives-ouvertes.fr/hal-01496854.

[3] P. DEGOND, P. MINAKOWSKI, L. NAVORET, E. ZATORSKA.*Finite volume approximations of the Euler system with variable congestion*, in "Computers & Fluids", September 2017, p. 1-29 [*DOI :* 10.1016/J.COMPFLUID.2017.09.007], https://hal.archives-ouvertes.fr/hal-01651479.

[4] E. FRANCK, L. GOSSE.*Stability of a Kirchhoff–Roe scheme for two-dimensional linearized Euler systems*, in "Annali dell'Universita di Ferrara", December 2017, p. 1-26 [*DOI :* 10.1007/S11565-017-0296-9], https://hal.archives-ouvertes.fr/hal-01666060.

[5] G. LATU, M. MEHRENBERGER, Y. GÜÇLÜ, M. OTTAVIANI, E. SONNENDRÜCKER.*Field-aligned interpolation for semi-Lagrangian gyrokinetic simulations*, in "Journal of Scientific Computing", August 2017, https://hal.archives-ouvertes.fr/hal-01315889.

International Conferences with Proceedings

[6] Y. A. BARSAMIAN, S. A. HIRSTOAGA, E. VIOLARD.*Efficient Data Structures for a Hybrid Parallel and Vectorized Particle-in-Cell Code*, in "IPDPSW 2017 - IEEE International Parallel and Distributed Processing Symposium Workshops", Lake Buena Vista, FL, United States, May 2017, p. 1168-1177 [*DOI :* 10.1109/IPDPSW.2017.74], https://hal.inria.fr/hal-01504645.

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[8] M. SCHMITT, P. HELLUY, C. BASTOUL.*Adaptive Code Refinement: A Compiler Technique and Extensions to Generate Self-Tuning Applications*, in "HiPC 2017 - 24th International Conference on High Performance Computing, Data, and Analytics", Jaipur, India, December 2017, https://hal.inria.fr/hal-01655459.

Conferences without Proceedings

[9] L. NAVORET, M. MEHRENBERGER.*About recurrence time for a semi-Lagrangian discontinuous Galerkin Vlasov solver*, in "Collisionless Boltzmann (Vlasov) Equation and Modeling of Self-Gravitating Systems and Plasmas", Marseille, France, October 2017, https://hal.archives-ouvertes.fr/hal-01653023.

[10] B. WEBER, P. HELLUY, T. STRUB.*Optimization of a Discontinuous Galerkin algorithm in OpenCL applied to electromagnetism simulation*, in "NUMELEC 2017 - 9th European Conference on Numerical Methods in Electromagnetics", Paris, France, November 2017, p. 1-2, https://hal.archives-ouvertes.fr/hal-01666352.

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[11] N. BOUZAT, F. ROZAR, G. LATU, J. ROMAN.*A new parallelization scheme for the Hermite interpolation based gyroaverage operator*, Inria, April 2017, n^{o} RR-9054, 22, https://hal.inria.fr/hal-01502513.

Other Publications

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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

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Project-Team VERIDIS

Creation of the Team: 2010 January 01, updated into Project-Team: 2012 July 01

Keywords:

Computer Science and Digital Science:

A2.1.7. - Distributed programming
A2.1.11. - Proof languages
A2.4. - Verification, reliability, certification
A2.4.1. - Analysis
A2.4.2. - Model-checking
A2.4.3. - Proofs
A7.2. - Logic in Computer Science
A8.4. - Computer Algebra

Other Research Topics and Application Domains:

B6.1. - Software industry
B6.3.2. - Network protocols
B6.6. - Embedded systems

1. Personnel

Research Scientists

Jasmin Christian Blanchette [Inria, Starting Research Position, until Feb 2017; external collaborator from Mar 2017]
Stephan Merz [Team leader, Inria, Senior Researcher, HDR]
Thomas Sturm [CNRS, Senior Researcher, HDR]
Sophie Tourret [Max-Planck Institut für Informatik, Researcher, from Oct 2017]
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. de Lorraine, Associate Professor]
Pascal Fontaine [Univ. de Lorraine, Associate Professor]
Dominique Méry [Univ. de Lorraine, Professor, HDR]
Martin Strecker [Univ. Paul Sabatier Toulouse, Associate Professor, Inria secondment until Aug 2017]

Technical Staff

Simon Cruanes [Inria, until Sep 2017]
Martin Riener [Inria, Microsoft-Inria Joint Centre]

PhD Students

Haniel Barbosa [Univ. de Lorraine, until Oct 2017]
Martin Bromberger [Univ. des Saarlandes]
Margaux Duroeulx [Univ. de Lorraine]
Daniel El Ouraoui [Inria, intern from Mar 2017 until Aug 2017 and PhD student from Oct 2017]
Mathias Fleury [Univ. des Saarlandes]
Souad Kherroubi [Univ. de Lorraine]
Nicolas Schnepf [Inria, joint with Team Madynes]
Hans-Jörg Schurr [Inria, from Nov 2017]

Andreas Teucke [Univ. des Saarlandes]
Marco Voigt [Univ. des Saarlandes]
Daniel Wand [Univ. des Saarlandes, until Jul 2017]

Visiting Scientists
Andrew Reynolds [Univ. of Iowa, from Jul 2017 until Sep 2017]
Tung Vu Xuan [JAIST Kanazawa, until May 2017]

Administrative Assistants
Sophie Drouot [Inria]
Christelle Levêque [Univ. de Lorraine]
Jennifer Müller [Max-Planck Institut für Informatik]

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 [52]. The group also studies general frameworks for the combination of theories such as the locality principle [64] 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 [0] 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 decision procedures 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^+ [59] 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* [49], [53], [60] in state-based

[0] Satisfiability Modulo Theories [54]

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, 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 have been 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, Mathias Fleury, and Christoph Weidenbach were invited to submit a short version of their IJCAR 2016 paper “A Verified SAT Solver Framework with Learn, Forget, Restart, and Incrementality” (which had received the Best Paper Award) to the Sister Conference Best Paper Track of IJCAI 2017 [25]. The paper was also invited to a special issue of *Logical Methods in Computer Science*.

The paper “A Formal Proof of the Expressiveness of Deep Learning” [22] by Jasmin Blanchette et al., presented at ITP 2017, has been invited to a special issue of the *Journal of Automated Reasoning*.

The paper “Decidability of the Monadic Shallow Linear First-Order Fragment with Straight Dismatching Constraints” [39] by Andreas Teucke and Christoph Weidenbach presented at CADE 26 has been invited to a special issue of the *Journal of Automated Reasoning*.

Two systems developed in the context of the SMArT project were submitted to the SMT competition SMT-COMP 2017. Redlog won the non-linear real arithmetic (NRA) category, and veriT+Redlog performed nicely on the quantifier-free non-linear real arithmetic (QF_NRA) category.

6. New Software and Platforms

6.1. Redlog

Reduce Logic System
KEYWORDS: Computer algebra system (CAS) - First-order logic - Constraint solving
SCIENTIFIC 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.
NEWS OF THE YEAR: In 2017, there was a strong focus on applications of Redlog. With the final phase of the ANR-DFG Project SMArT, Redlog was integrated with the SMT solver veriT. That combination, as well as a stand-alone version of Redlog, participated in the SMT competition SMTCOMP 2017. All configurations performed very well, the stand-alone version won the category NRA (nonlinear real arithmetic).

On the scientific side, we made significant progress with the symbolic bifurcation analysis for biological networks.

Redlog technology for biological network analysis from last year, viz. subtropical solving, has raised considerable attention in the SMT community, where it has been adopted and triggered new research.

- Participant: Thomas Sturm
- Contact: Thomas Sturm
- URL: http://www.redlog.eu/

6.2. SPASS

KEYWORD: First-order logic
SCIENTIFIC 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. Furthermore, we use SPASS 3.9 as a test bed for the development of new calculi.

Meanwhile we have released the second version of SPASS-IQ, our solver for linear integer arithmetic that we are currently extending to real and mixed real-integer arithmetic. We didn't release SPASS-SATT yet, instead we further investigated the use of redundency elimination in SAT solving and underlying implementation techniques. Our aim is a new approach to SAT solving that needs fewer conflicts (on average) *and* is faster than the current state-of-the art solvers. Furthermore, we have developed a new calculus and first prototypical implementation of a SAT solver with mixed OR/XOR clauses.

SPASS 3.9 has been used as the basis for SPASS-AR, an new approximation refinement theorem proving approach.
FUNCTIONAL DESCRIPTION: SPASS is an automated theorem prover based on superposition that handles first-order logic with equality and several extensions for particular classes of theories.

- Contact: Christoph Weidenbach
- URL: http://www.spass-prover.org/

6.3. TLAPS

TLA+ proof system
KEYWORD: Proof assistant
FUNCTIONAL DESCRIPTION: TLAPS 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 proof steps that can be checked independently. 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+ set theory 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.
NEWS OF THE YEAR: In 2017, we have continued to work on a complete reimplementation of the proof manager. Its objectives are a cleaner interaction with the TLA^+ front-ends, in particular SANY, the standard parser and semantic analyzer. The reimplementation is also necessary for extending the scope of the fragment of TLA^+ that is handled by TLAPS, in particular full temporal logic and module instantiation.

- Participants: Damien Doligez, Stephan Merz and Martin Riener
- Contact: Stephan Merz
- URL: https://tla.msr-inria.inria.fr/tlaps/content/Home.html

6.4. veriT

KEYWORDS: Automated deduction - Formula solving - Verification
SCIENTIFIC DESCRIPTION: veriT comprises a SAT solver, a decision procedure for uninterpreted symbols based on congruence closure, 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.
NEWS OF THE YEAR: Efforts in 2017 have been focused on non-linear arithmetic reasoning and quantifier handling. The reasoning capabilities of veriT have been significantly improved along those two axes.

The veriT solver participated in the SMT competition SMT-COMP 2017 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: Haniel Barbosa, Daniel El Ouraoui, Pascal Fontaine and Hans-Jörg Schurr
- Partner: Université de Lorraine
- Contact: Pascal Fontaine
- URL: http://www.veriT-solver.org

6.5. Nunchaku

The Nunchaku Higher-Order Model Finder
KEYWORDS: Proof - Higher-order logic
SCIENTIFIC 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 (notably Isabelle/HOL and Coq) and to use state-of-the-art model finders and other solvers as backends.
FUNCTIONAL DESCRIPTION: Nunchaku is a model finder (counterexample generator) for higher-order logic.
NEWS OF THE YEAR: A noteworthy development this year is the creation of a backend called SMBC, based on new ideas by Cruanes about how to combine SAT solving and narrowing.

- Participants: Jasmin Christian Blanchette and Simon Cruanes
- Contact: Jasmin Christian Blanchette
- URL: https://github.com/nunchaku-inria

7. New Results

7.1. Automated and Interactive Theorem Proving

Participants: Haniel Barbosa, Jasmin Christian Blanchette, Martin Bromberger, Simon Cruanes, Daniel El Ouraoui, Mathias Fleury, Pascal Fontaine, Stephan Merz, Martin Riener, Hans-Jörg Schurr, Martin Strecker, Thomas Sturm, Andreas Teucke, Sophie Tourret, Marco Voigt, Tung Vu Xuan, Uwe Waldmann, Daniel Wand, Christoph Weidenbach.

7.1.1. IsaFoL: Isabelle Formalization of Logic

Joint work with Andreas Halkjær From (DTU Copenhagen), Alexander Birch Jensen (DTU Copenhagen), Maximilian Kirchmeier (TU München), Peter Lammich (TU München), John Bruntse Larsen (DTU Copenhagen), Julius Michaelis (TU München), Tobias Nipkow (TU München), Nicolas Peltier (IMAG Grenoble) 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*.

[0] https://bitbucket.org/isafol/isafol/wiki/Home

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.

The repository contains 14 completed entries and four entries that are still in development. Notably, Mathias Fleury formalized a SAT solver framework with learn, forget, restart, and incrementality. This year he extended it with key optimizations such as the two-watched-literal procedure. The corresponding paper, written together with Jasmin Blanchette and Peter Lammich, was accepted at a highly competitive conference (CPP 2018).

7.1.2. Extension of Term Orders to λ-Free Higher-Order Logic

Superposition is one of the most successful proof calculi for first-order logic today, but in contrast to resolution, tableaux, and connections, it has not yet been generalized to higher-order logic (also called simple type theory). Yet, most proof assistants and many specification languages are based on some variant of higher-order logic.

This motivates us to design a *graceful* generalization of superposition: a proof calculus that behaves like standard superposition on first-order problems and that smoothly scales up to arbitrary higher-order problems. A challenge is that superposition relies on a simplification order, which is fixed in advance of the proof attempt, to prune the search space.

We started our investigations by focusing on a fragment devoid of λ-abstractions, but with partial application and application of variables, two crucial higher-order features. We generalized the two main orders that are used in superposition-based provers today—the lexicographic path order (LPO) [27] and the Knuth-Bendix order (KBO) [21]. The new orders gracefully generalize their first-order counterparts and enjoy nearly all properties needed for superpositions. An exception is compatibility with contexts, which is missing for LPO and some KBO variants. Preliminary work suggests that we can define a version of the superposition calculus that works well in theory and practice (i.e., is refutationally complete and does not lead to a search-space explosion) despite the missing property.

7.1.3. A Fine-Grained Approach of Understanding First-Order Logic Complexity

By the introduction of the separated fragment [65] we have initiated a new framework for a fine-grained understanding of the complexity of fragments of first-order logic, with and without the addition of theories. We have related the classes of the polynomial hierarchy to subclasses of the separated fragment [40] and developed new decidability results [36], [41] based on the techniques of our framework for the combination of the Bernays-Schoenfinkel subfragment with linear arithmetic.

7.1.4. Theorem Proving Based on Approximation-Refinement into the Monadic Shallow Linear Fragment with Straight Dismatching Constraints

We have introduced an approximation-refinement approach for first-order theorem proving based on counterexample-guided abstraction refinement [39]. A given first-order clause set is transformed into an over-approximation contained in the fragment of monadic, shallow, linear clauses with straight dismatching constraints. We have shown the fragment to be decidable, strictly extending known results. If the abstraction obtained that way is satisfiable, so is the original clause set. However, if it is unsatisfiable, then the approximation provides a terminology for lifting the found refutation, step by step, into a proof for the original clause set. If lifting fails, the cause is analyzed to refine the original clause set such that the found refutation is ruled out for the future, and the procedure repeats. We have shown that this approach is superior to all known calculi on certain classes of first-order clauses. In particular, it is able to detect satisfiability of clause sets that have only infinite models.

7.1.5. Combination of Satisfiability Procedures

Joint work with Christophe Ringeissen from the PESTO project-team of 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 difficult, 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 [55] 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 other theories [56] amenable to similar combinations: this class includes the theory of equality, the theory of absolutely free data structures, and all the theories in between.

In 2017, we have been improving the framework and unified both results. A new paper is in preparation.

7.1.6. Quantifier Handling in SMT

Joint work with Andrew J. Reynolds, Univ. of Iowa, USA.

SMT solvers generally rely on various instantiation techniques for handling quantifiers. We built a unifying framework encompassing 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 demonstrate notable improvements in the state-of-the-art solver CVC4 and make the solver veriT competitive with state-of-the-art solvers for several benchmark libraries, in particular those originating in verification problems. This was the subject of a publication [20]. In later, unpublished work, we are revisiting enumerative instantiation for SMT. This effort takes place in the context of the Matryoshka project.

7.1.7. Non-Linear Arithmetic in SMT

In the context of the SMArT ANR-DFG (Satisfiability Modulo Arithmetic Theories), KANASA and SC^2 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, notably in the international competition of SMT solvers SMT-COMP 2017. We also studied 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.

We also adapted the subtropical method to use in an SMT context, with valuable results. This was the subject of a publication in 2017 [33].

7.1.8. Proofs for SMT

We have developed a framework for processing formulas in automatic theorem provers, with generation of detailed proofs. The main components are a generic contextual recursion algorithm and an extensible set of inference rules. Clausification, skolemization, theory-specific simplifications, and expansion of 'let' expressions are instances of this framework. With suitable data structures, proof generation adds only a linear-time overhead, and proofs can be checked in linear time. We implemented the approach in the SMT solver veriT. This allowed us to dramatically simplify the code base while increasing the number of problems for which detailed proofs can be produced, which is important for independent checking and reconstruction in proof assistants. This was the subject of a publication in [19]. This effort takes place in the context of the Matryoshka project.

7.1.9. Coding Modal and Description Logics in SAT solvers

The application scenario behind this research is the verification of graph transformations, which themselves are relevant for a wide range of practical problems such as pointer structures in imperative programs, graph databases or access control mechanisms.

Graph structures can typically be perceived as models of modal logics, and modal logics and variants (such as description logics that are the basis for the web ontology language OWL) are in principle suitable specification formalisms for graph transformations. It turns out, however, that pure modal logics are often not sufficiently expressive for the intended verification purpose and that extensions are needed for which traditional proof methods such as tableau calculi become complex: the termination of the calculi are often very difficult to prove, and huge efforts are required to obtain an efficient implementation.

For these reasons, we have explored methods of encoding the above-mentioned logics in SAT and SMT solvers such as CVC4 and veriT. The idea is to traverse the formula to be verified in order to span up a pre-model that possibly contains more elements (worlds in a Kripke structure) than the real model, and then to run a solver to find out which of these elements can effectively be realized. A prototype has been implemented, with encouraging results. It remains to connect this prototype to the graph verification engine and to publish this work.

7.1.10. Work on the TLA+ Proof System

We continued our work on encoding set-theoretic formulas in multi-sorted first-order logic, and in particular for SMT solvers. Specifically, we unified and streamlined a technique combining an injection of unsorted expressions into sorted languages, simplification by rewriting, and abstraction that underlies the SMT backend of the TLA^+ proof system TLAPS. A presentation of our technique was accepted in the journal *Science of Computer Programming*, to appear in 2018.

The proof of the join protocol in a pure-join variant of the Pastry protocol [63] implementing a distributed hash table over a peer-to-peer network is the largest case study carried out so far within TLAPS. Consisting of roughly 30k lines of proof, it was developed as part of Noran Azmy's PhD thesis, defended at the end of 2016 [51]. A presentation of the design of the protocol and its proof was accepted in the journal *Science of Computer Programming*, to appear in 2018.

7.1.11. Automated Analysis of Systems of ODE for Multistationarity

Joint work with R. Bradford and J. Davenport (Bath, UK), M. England (Coventry, UK), H. Errami, C. Hoyt, and A. Weber (Bonn, Germany), V. Gerdt (Dubna, Russia), D. Grigoriev (Lille, France), O. Radulescu (Montpellier, France)

We considered the problem of determining multiple steady states for positive real values in models of biological networks. Investigating the potential for these in models of the mitogen-activated protein kinases (MAPK) network has consumed considerable effort using special insights into the structure of corresponding models. We have applied combinations of symbolic computation methods for mixed equality/inequality systems, specifically automated deduction methods like virtual substitution, lazy real triangularization and cylindrical algebraic decomposition. We have determined multistationarity of an 11-dimensional MAPK network when numeric values are known for all but potentially one parameter. More precisely, our considered model has 11 equations in 11 variables and 19 parameters, 3 of which are of interest for symbolic treatment, and furthermore positivity conditions on all variables and parameters [28].

Subsequent work [31] demonstrates that our techniques benefit tremendously from a new graph theoretical symbolic preprocessing method. We apply our combined techniques to visualize of parameter regions for multistationarity. Comparing computation times and quality of results it turns out that our automated deduction-based approach clearly outperforms established numerical continuation methods.

While automated deduction technology is a bit under the hood here, this interdisciplinary research line addresses important questions related to contemporary research in systems biology. With researchers from that area very actively involved, the results are recognized also within their communities.

7.2. Formal Methods for Developing and Analyzing Algorithms and Systems

Participants: Marie Duflot-Kremer, Margaux Duroeulx, Souad Kherroubi, Poonam Kumari, 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.

As explained in the description of the IMPEX project in section 9.1, we advocate that formal modeling languages should explicitly represent the knowledge resulting from an analysis of the application domain, and that ontologies are good candidates for handling explicit domain knowledge. Our objective in doing so is to offer rigorous mechanisms for handling domain knowledge in design models.

We developed the notion of dependency for state-based models. Context-awareness is an important feature in system design. We argue that in proof systems and conceptual modelling this notion should be highlighted precisely. Since we focus on conceptual modelling, understandability and clarity are of high importance. We introduce a new definition [37] for proof context in state-based formalisms with an application to the Event-B modeling language. Furthermore, we introduce a dependency relation between two Event-B models. The contextualization of Event-B models is based on knowledge provided from domains that we classified into constraints, hypotheses and dependencies. The dependency mechanism between two models makes it possible to structure the development of systems models, by organizing phases identified in the analyzed process. These ideas are inspired by work based on the modelling of situations in situation theory that emphasize capabilities of type theory with regard to situation modelling to represent knowledge. Our approach is illustrated on small case studies, and was validated on a development of design patterns for voting protocols.

7.2.2. Incremental Development of Systems and Algorithms

Joint work with Manamiary Bruno Andriamiarina, Neeraj Kumar Singh (IRIT, Toulouse), Rosemary Monahan (NUI Maynooth, Ireland), Zheng Cheng (LINA, Nantes), and Mohammed Mosbah (LaBRI, Bordeaux).

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 result during 2017 is the development of a proved-based pattern for integrating the local computation models and the Visidia platform [32].

7.2.3. Modeling Network Flows in View of Building Security Chains

Joint work with Rémi Badonnel and Abdelkader Lahmadi of the Madynes team of Inria Nancy – Grand Est.

We are working on the application of formal modeling and verification techniques in the area of network communications, and in particular for constructing security functions in a setting of software-defined networks (SDN). Concretely, Nicolas Schnepf defined an extension of the Pyretic language [58] taking into account both the control and the data planes of SDN controllers and implemented a translation of that extension to the input languages of the nuXmv model checker and of SMT solvers. This work was published at NetSoft 2017 [38].

Extending this approach, we have worked on inferring probabilistic finite-state automata models that represent network flows generated by Android applications. The objective is to exploit this representation for generating security chains that detect significant deviations from the behavior represented by the automata and can initiate protective actions. Comparing our models with automata produced by the state-of-the-art tools Invarimint and Synoptic, we obtain representations that are as succinct as those inferred by Invarimint, and significantly smaller than Synoptic, but that include information about transition probability, which Invarimint does not. This work was accepted for publication at NOMS 2018.

7.2.4. Satisfiability Techniques for Reliability Assessment

Joint work with Nicolae Brînzei at Centre de Recherche en Automatique de Nancy.

The reliability of complex systems is typically assessed using probabilistic methods, based on the probabilities of failures of individual components, relying on graphical representations such as fault trees or reliability block diagrams. Mathematically, the dependency of the overall system on the working status of its components is described by its Boolean-valued *structure function*, and binary decision diagrams (BDDs) have been used to construct a succinct representation of that function. We explore the use of modern satisfiability techniques as an alternative to BDD-based algorithms. In [30], we develop three different algorithms for computing minimal tie sets (i.e., component configurations that ensure that the system is functioning). Our algorithms are based on either conjunctive or disjunctive normal form representations of the structure function or on the Hasse diagram representing the configurations. These algorithms have been prototypically implemented in Python, and we are evaluating them on existing benchmarks in order to understand which algorithm works best for typical fault dependencies.

7.2.5. Statistical evaluation of the robustness of production schedules

Joint work with Alexis Aubry, Sara Himmiche, Pascale Marangé, and Jean-François Pétin at Centre de Recherche en Automatique de Nancy.

Finding a good schedule for a production system, especially when it is flexible and when several machines can perform the same operation on products, is a challenging and interesting problem. For a long time, operations research has provided state-of-the-art methods for optimizing scheduling problems. However, approaches based on Discrete Event Systems present interesting alternatives, especially when dealing with uncertainties on the demand or the production time. In this particular case, the flexibility of the automata-based modeling approach is really useful. Using probabilistic timed automata, we demonstrated [35] that statistical model checking can be used successfully for evaluating the robustness of a given schedule w.r.t. probabilistic variations of the processing time. We were thus able to compare different schedules based on their level of service (i.e., the probability that the system will complete the production process within a deadline slightly higher that the schedule time) and their sensitivity (the minimal deadline for which the level of service is greater than a given threshold) [42].

An interdisciplinary workshop on this topic was organized jointly with our colleagues of Centre de Recherche en Automatique and funded by Fédération Charles Hermite.

7.2.6. Using Cubicle for Verifying TLA+ Specifications

Cubicle [0] is a model checker for the verification of parameterized transition systems whose state is described by arrays of variables indexed by an abstract sort representing processes. During her internship, Poonam Kumari designed a translation algorithm from a restricted class of TLA$^+$ specifications into the input language of Cubicle. A prototypical implementation demonstrates the feasibility of the approach, although more work will be necessary to widen the scope of the translation. This work will be continued within the PARDI project, described in section 9.1.

8. Bilateral Contracts and Grants with Industry

8.1. Modeling a Distributed File System

Participant: Stephan Merz.

In a bilateral contract with Huawei R&D, we continued our work on modeling and verifying protocols underlying the Ceph distributed file system [66] in TLA$^+$. We also provided email support to Huawei engineers who use TLA$^+$ for modeling the systems they develop.

[0] http://cubicle.lri.fr

8.2. Modeling a Distributed Development Process

Participant: Christoph Weidenbach.

On the basis of a bilateral contract with L4B (Logic 4 Business), we studied models for a distributed development process of a leading German car manufacturer.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. ANR-DFG Project SMArT

Participants: Haniel Barbosa, Pascal Fontaine, Stephan Merz, Thomas Sturm.

The SMArT (Satisfiability Modulo Arithmetic Theories) project was funded by ANR-DFG Programmes blancs 2013, a bilateral (French-German) program of Agence Nationale de la Recherche and Deutsche Forschungsgemeinschaft DFG. It started in April 2014 and finished in September 2017. The project gathered members of VeriDis in Nancy and Saarbrücken, and the Systerel company.

The objective of the SMArT project was 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 and veriT, 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 was 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 focus on the analysis of the designed system, exploiting the semantic power of the underlying modeling language. The semantics of this modeling languages are well understood by its users (in particular the system designers), 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 [61], i.e. explicit semantics. At present, 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 [50] is to offer rigorous mechanisms for handling domain knowledge in design models.

9.1.3. ANR Project Formedicis

Participant: Dominique Méry.

The ANR Project Formedicis, within the INS program, started in January 2017 for 4 years. It is coordinated by Bruno d'Augsbourg, the partners are ONERA, IRIT/ENSEIHT, ENAC, and LORIA.

During the last 30 years, the aerospace domain has successfully devised rigorous methods and tools for the development of safe functionally-correct software. During this process, interactive software has received a relatively lower amount of attention. However, Human-System Interactions (HSI) are important for critical systems and especially in aeronautics: new generations of aircraft cockpits make use of sophisticated electronic devices that may be driven by more and more complex software applications. The criticality of these applications require a high degree of assurance for their intended behavior. The report by the French *Bureau d'Enquêtes et d'Analyses* about the crash of the Rio-Paris flight AF 447 in 2009 pointed out a design issue in the behavior of the Flight Director interface as one of the original causes of the crash.

We believe that part of these issues are due to the lack of a well-defined domain specific "hub" language to represent interactive software design in a way that allows system designers to iterate on their designs before injecting them in a development process, and system developers to verify their software against the chosen design. Formedicis aims at designing such a formal hub language L, in which designers can express their requirements concerning the interactive behavior that must be embedded inside the interactive applications. The project will also develop a framework for validating, verifying, and implementing critical interactive applications designed and denoted in L.

More information on the project is available at http://www.agence-nationale-recherche.fr/Project-ANR-16-CE25-0007.

9.1.4. ANR Project PARDI

Participants: Marie Duflot-Kremer, Stephan Merz.

PARDI (Verification of parameterized distributed systems) is funded by ANR. The project started in January 2017 for a duration of 48 months. The project partners other than VeriDis are Toulouse INP (coordinator), Université Paris Sud, and Université Paris Marie Curie.

Distributed systems and algorithms are parameterized by the number of participating processes, the communication model, the fault model, and more generally the properties of interaction among the processes. The project aims at providing methodological and tool support for verifying parameterized systems, using combinations of model checking and theorem proving. VeriDis contributes its expertise on TLA$^+$ and its verification tools, and the integration with the Cubicle model checker is a specific goal of the project.

More information on the project is available at http://pardi.enseeiht.fr/.

9.1.5. 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.

9.1.6. 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, supported the development of a counterexample generator for higher-order logic. This new tool, called Nunchaku, is intended for integration with various proof assistants. The project was coordinated by Jasmin Blanchette and also involved Inria Saclay – Île de France (Toccata group) and Inria Rennes – Bretagne

Atlantique (Celtique group), among others. Simon Cruanes worked on Nunchaku from October 2015 to September 2017, whereas Blanchette has developed an Isabelle frontend. Four releases have taken place so far, and the tool is an integral part of the Isabelle2017 official release. Work has started on Coq and TLAPS frontends, and we will soon work on a Lean frontend as well. The tool is described in [62] and was presented at a workshop last year [57]. A noteworthy development this year is the creation of a backend called SMBC, based on new ideas by Cruanes about how to combine SAT solving and narrowing [29].

9.2. European Initiatives

9.2.1. FP7 & H2020 Projects

9.2.1.1. ERC Matryoshka

Program: European Union's Horizon 2020 research and innovation program

Project acronym: Matryoshka

Duration: April 2017 – March 2022

Coordinator: Jasmin Blanchette (VU Amsterdam)

Proof assistants are increasingly used to verify hardware and software and to formalize mathematics. However, despite the success stories, they remain very laborious to use. The situation has improved with the integration of first-order automatic theorem provers—superposition provers and SMT (satisfiability modulo theories) solvers—through middleware such as Sledgehammer for Isabelle/HOL and HOLyHammer for HOL Light and HOL4; but this research has now reached the point of diminishing returns. Only so much can be done when viewing automatic provers as black boxes.

To make interactive verification more cost-effective, we propose to deliver very high levels of automation to users of proof assistants by fusing and extending two lines of research: automatic and interactive theorem proving. This is our grand challenge. Our starting point is that first-order (FO) automatic provers are the best tools available for performing most of the logical work. Our approach will be to enrich superposition and SMT with higher-order (HO) reasoning in a careful manner, in order to preserve their desirable properties. We will design proof rules and strategies, guided by representative benchmarks from interactive verification.

With higher-order superposition and higher-order SMT in place, we will develop highly automatic provers building on modern superposition provers and SMT solvers, following a novel stratified architecture. To reach end users, these new provers will be integrated in proof assistants and will be available as backends to more specialized verification tools. The users of proof assistants and similar tools stand to experience substantial productivity gains: From 2010 to 2016, the success rate of automatic provers on interactive proof obligations from a representative benchmark suite called Judgment Day has risen from 47% to 77%; with this project, we aim at 90%–95% proof automation.

The Matryoshka ERC grant of Jasmin Blanchette includes Pascal Fontaine and Uwe Waldmann as senior researchers.

9.2.1.2. FET-Open CSA SC^2

Program: European Union's Horizon 2020 research and innovation program

Project acronym: SC^2

Project title: Symbolic Computation and Satisfiability Checking

Duration: July 2016 – August 2018

Coordinator: James Davenport (U. of Bath, UK)

Other partners: see http://www.sc-square.org/CSA/welcome.html

The use of advanced methods for solving practical and industrially relevant problems by computers has a long history. Whereas Symbolic Computation is concerned with the algorithmic determination of exact solutions to complex mathematical problems, more recent developments in the area of Satisfiability Checking tackle similar problems but with different algorithmic and technological solutions.

Though both communities have made remarkable progress in the last decades, they still need to be strengthened to tackle practical problems of rapidly increasing size and complexity. Their separate tools (computer algebra systems and SMT solvers) are urgently needed to examine prevailing problems with a direct effect to our society. For example, Satisfiability Checking is an essential backend for assuring the security and the safety of computer systems. In various scientific areas, Symbolic Computation enables dealing with large mathematical problems 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. However, researchers from these two communities rarely interact, and also their tools lack common, mutual interfaces for unifiying their strengths. 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. These are the main objectives of this CSA. We 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.

We believe that these activities will foster cross-fertilisation of both fields and bring mutual improvements. Combining the knowledge, experience and the technologies in these communities will enable the development of radically improved software tools.

This project is locally coordinated by Pascal Fontaine.

9.3. International Initiatives

9.3.1. Inria International Partners

Title: Kanazawa-Nancy for Satistifiability and Arithmetics (KANASA)

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.

One PhD student from JAIST spent one year in the VeriDiS team, until May 2017. The partnership evolves towards applying SMT to find malware in obfuscated code.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

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 was 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 investigated techniques to combine ICP with decision procedures for NLA within an SMT context, and adapted the subtropical method from computer algebra to the context of SMT. This work is relevant for the SMArT and SC^2 projects.

Andrew J. Reynolds

Date: 16 July 2017 – 17 September 2017

Institution: The University of Iowa

Host: Pascal Fontaine

Andrew J. Reynolds is a Research Scientist at the University of Iowa and one of main developers of the award-winning Satisfiability Modulo Theories (SMT) solver CVC4. His current research interests include implementing techniques in SMT solvers for unbounded strings and regular expressions, first-order quantified formulas and synthesis conjectures. He was an Inria invited researcher for two months in Nancy. We continued working on quantifier handling for SMT, along the lines of [20], and studied enumerative instantiation. This work contributes to the Matryoshka, SMArT and SC^2 projects.

9.4.2. Internships

Poonam Kumari

Date: 1 March – 31 July

Institution: Université de Lorraine (Erasmus Mundus DESEM)

Host: Stephan Merz

Poonam Kumari worked on a translation from a restricted subset of TLA^+ specifications into the input language of the Cubicle model checker for array-based parameterized systems.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Organization of Scientific Events

10.1.1.1. Member of the Organizing Committees

Jasmin Blanchette co-organized the *(Co)programming in Isabelle/HOL* tutorials at ICFP 2017 in Oxford, UK, and at CADE-26 in Gothenburg, Sweden.

Jasmin Blanchette co-organized the Dagstuhl Seminar on *Deduction beyond First-Order Logic* held at Schloss Dagstuhl in Germany.

Jasmin Blanchette co-organized the *(Co)programming in Isabelle/HOL* tutorials at ICFP 2017 in Oxford, UK, and at CADE-26 in Gothenburg, Sweden.

Dominique Méry was a member of the organizing committees of the workshops F-IDE [43] and IMPEX'2017.

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 2017, VTSA took place in July in Saarbrücken, Germany.

The SC^2 Summer School 2017 took place in Saarbrücken, Germany. It has been co-organized by Thomas Sturm. The school introduced graduate students and researchers from academia and industry into research and methodology in both Satisfiability Checking (SAT/SMT) and Symbolic Computation with one focus on their interconnections. It combined a thorough introduction into the theory of both fields with lectures on state-of-the-art software systems and their implementation. This was supplemented with presentations by lecturers from industry discussing the practical relevance of the topics of the school.

Together with the CADE trustees, Christoph Weidenbach started the first CADE workshop on *Automated Reasoning: Challenges, Applications, Directions, Exemplary Achievements* (ARCADE 2017)

10.1.2. Program Committees

10.1.2.1. Chair of Conference Program Committees

Stephan Merz co-chaired the program committee of the Fourth International Workshop on Formal Reasoning in Distributed Algorithms (FRiDA), organized in October 2017 as a satellite of DISC in Vienna, Austria.

10.1.2.2. Member of the Conference Program Committees

Jasmin Blanchette served on the program committees of the Conference on *Computer-Aided Verification* (CAV 2017), the *Conference on Automated Deduction* (CADE-26), the *International Conference on Tests and Proofs* (TAP 2017), and the Conference on *Artificial Intelligence and Theorem Proving* (AITP 2017). He also served on the following workshop committees: *Automated Reasoning: Challenges, Applications, Directions, Exemplary Achievements* (ARCADE 2017), *International Workshop on the Implementation of Logics* (IWIL 2017), *Proof Exchange for Theorem Proving* (PxTP 2017), and *Satisfiability Modulo Theories* (SMT 2017).

Pascal Fontaine served on the program committees of the *International Symposium on Frontiers of Combining Systems* (FroCoS 2017), the *Conference on Automated Deduction* (CADE-26) and the *International Conference on Automated Reasoning with Analytic Tableaux and Related Methods* (TABLEAUX 2017). He also served on the following workshop committees: *Automated Reasoning: Challenges, Applications, Directions, Exemplary Achievements* (ARCADE 2017), *Satisfiability Modulo Theories* (SMT 2017), *Satisfiability Checking and Symbolic Computation* (SC^2 2017), *Proof Exchange for Theorem Proving* (PxTP 2017)

Stephan Merz served on the program committees of the international conferences *Formal Techniques for Distributed Objects, Components, and Systems* (FORTE 2017), *Foundations of Software Technology and Theoretical Computer Science* (FSTTCS 2017), and *Formal Engineering Methods* (ICFEM 2017), the national conference *Modélisation des Systèmes Réactifs* (MSR 2017), and of the workshops FMICS-AVoCS and GRSRD.

Thomas Sturm served on the program committees of the *Second International Workshop on Satisfiability Checking and Symbolic Computation* (SC^2 2017) and the *19th International Workshop on Computer Algebra in Scientific Computing* (CASC 2017).

Uwe Waldmann served on the program committee of the workshop *International Workshop on the Implementation of Logics* (IWIL 2017) colocated with LPAR.

Christoph Weidenbach served on the program committees of the *Conference on Automated Deduction* (CADE-26) and the *International Symposium on Frontiers of Combining Systems* (FroCoS 2017). He also served on the workshop committee *Automated Reasoning: Challenges, Applications, Directions, Exemplary Achievements* (ARCADE 2017).

10.1.3. Journals

Jasmin Blanchette and Stephan Merz are the editors of a special issue of *Journal of Automated Reasoning* following the international conference *Interactive Theorem Proving* 2016.

Dominique Méry is the review book editor of the journal *Formal Aspects for 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 a member of the editorial board of the *Journal of Automated Reasoning* (Springer).

10.1.4. Invited Talks

Jasmin Blanchette was invited to give a joint keynote talk at the FroCoS 2017, ITP 2017, and TABLEAUX 2017 conferences held in Brasília, Brazil. He presented Isabelle/HOL's support for (co)datatypes and (co)recursion [18]. He also gave invited seminar talks at the Big Proof Workshop organized by the Isaac Newton Institute in Cambridge, UK, at the TeReSe (Term Rewriting Systems) meeting in Eindhoven, the Netherlands, and at the Shonan Meeting on Automated Deduction at the Shonan Village Center in Japan.

Stephan Merz gave an invited presentation on "Formal Methods for the Cloud" at the Cloud Resiliency Workshop 2017 in Shenzhen, China.

Thomas Sturm was invited to give a keynote talk at the *3ème BIOSS Journées annuelles du groupe de travail* in Montpellier, France.

Uwe Waldmann gave an invited talk on "Saturation Theorem Proving – Basic Ideas, History, and Recent Developments" at the Seminar on Proof Assistants and Related Tools at DTU Lyngby, Denmark in October 2017.

Christoph Weidenbach gave invited talks on "Design Principles of Automated Reasoning Systems" at VSTTE 2017 and "The Role of Horn Clauses in Automatic Reasoning" at HCVS 2017.

10.1.5. Leadership within the Scientific Community

Jasmin Blanchette was elected as a regular member of the steering committee for the ITP (*Interactive Theorem Proving*) conference series, after serving for two years as an ex officio member. He is also a regular member of the CADE (*Conference on Automated Deduction*) Inc. Board of Trustees.

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 was an elected CADE trustee since October 2014 until October 2017 and served as a member of the Association for Automated Reasoning (AAR) board until October 2017.

Stephan Merz is a member of the IFIP Working Group 2.2 on *Formal Description of Programming Concepts*. He is a member of the steering committee of the workshop on Automated Verification of Critical Systems (AVoCS).

Thomas Sturm has been a member of the steering committee of the conference series *International Conference on Mathematical Aspects of Computer and Information Sciences (MACIS).* His term ended in November 2017. In July 2017 he was elected as a member at large of the steering committee of the conference series *International Symposium on Symbolic and Algebraic Computation (ISSAC).*

Christoph Weidenbach is the president of CADE and a member of the steering committee of IJCAR.

10.1.6. Scientific Expertise

Pascal Fontaine was a panel member for the CASC-26 competition of first-order theorem prover. He served as an expert for the French Agence Nationale de la Recherche (ANR).

Stephan Merz served as an expert for the French Agence Nationale de la Recherche (ANR) and for the European Research Council (ERC).

Christoph Weidenbach served as an expert for the Austrian Science Fund and the University of Stellenbosch.

10.1.7. Research Administration

Dominique Méry was the head of the Doctoral School IAEM Lorraine of University of Lorraine until September 2017.

Stephan Merz is the delegate for scientific affairs at the Inria Nancy – Grand Est research center and a member of Inria's Evaluation Committee. In 2017, he was a member of the hiring committees of junior researchers at Inria Saclay – Île de France as well as of senior researchers at Inria. He is a member of the committee for the SIF thesis award (*Prix Gilles Kahn*). He is a member of the *bureau* of the computer science committee of the doctoral school IAEM Lorraine. Until October 2017, he was a member of the Scientific Directorate of the International Computer Science Meeting Center in Schloss Dagstuhl.

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, Logical Verification, 36 HETD, M1/M2, Vrije Universiteit Amsterdam, the Netherlands.

Licence: Marie Duflot-Kremer, Algorithmique et Programmation 1, 70 HETD L1 Mathématiques, Informatiques Sciences pour l'Ingénieur, Université de Lorraine, France.

Licence: Marie Duflot-Kremer, Bases de données 2, 20 HETD, L2 Informatique, Université de Lorraine, France.

Licence: Marie Duflot-Kremer, Projet personnel et communication, 60 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, 40 HETD, M2 Informatique, Université de Lorraine, France.

Master : Marie Duflot-Kremer and Stephan Merz, Conception et architectures distribuées 24 HETD M1 informatique, Université de Lorraine, France.

Licence : Pascal Fontaine, Structure des ordinateurs, 47 HETD, L2 MIASHS, parcours MIAGE, 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, Ireland.

Master: Stephan Merz, Modeling and Verifying Distributed Algorithms in TLA$^+$, 8 HETD, NUI Maynooth, Ireland.

Master: Christoph Weidenbach, Automated Reasoning I & II, 150 HETD, Universität des Saarlandes, Germany.

10.2.2. Supervision

PhD: Haniel Barbosa, New techniques for instantiation and proof production in SMT solving, Université de Lorraine and UFRN (Natal, Brazil) [11]. Supervised by David Déharbe, Pascal Fontaine, and Stephan Merz, since 12/2013. Defended on September 5, 2017.

PhD: Andreas Teucke, *An Approximation and Refinement Approach to First-Order Automated Reasoning*, Saarland University. Supervised by Christoph Weidenbach, thesis submitted in October 2017.

PhD: Daniel Wand, First-Order Extensions to Support Higher-Order Reasoning, Saarland University [12]. Supervised by Christoph Weidenbach and Jasmin Blanchette, since 02/2011. Defended on August 4, 2017.

PhD in progress: Martin Bromberger, Arithmetic Reasoning, Saarland University. Supervised by Christoph Weidenbach, since July 2014.

PhD in progress: Margaux Duroeulx, SAT Techniques for Reliability Assessment, Université de Lorraine. Supervised by Nicolae Brînzei, Marie Duflot-Kremer, and Stephan Merz, since October 2016.

PhD in progress: Daniel El Ouraoui, Higher-Order SMT, Université de Lorraine. Supervised by Jasmin Blanchette, Pascal Fontaine, and Stephan Merz, since November 2017.

PhD in progress: Mathias Fleury, Formalization of Logical Calculi, Saarland University. Supervised by Christoph Weidenbach and Jasmin Blanchette, since September 2015.

PhD in progress: Souad Kherroubi, A framework to formally handle domain knowledge in system design, Université de Lorraine. Supervised by Dominique Méry, since November 2014.

PhD in progress: Nicolas Schnepf, Orchestration and Verification of Security Functions for Smart Environments, Université de Lorraine. Supervised by Rémi Badonnel, Abdelkader Lahmadi, and Stephan Merz, since October 2016.

PhD in progress: Hans-Jörg Schurr, Higher-Order SMT, Université de Lorraine. Supervised by Jasmin Blanchette, Pascal Fontaine, and Stephan Merz, since November 2017.

PhD in progress: Marco Voigt, Decidable Hierarchic Combinations, Saarland University. Supervised by Christoph Weidenbach, since November 2013.

10.2.3. Thesis committees

Stephan Merz served as a reviewer for the PhD theses of Florent Chevrou (Univ. de Toulouse), Sebastian Krings (Univ. Düsseldorf), Ognjen Marič (ETH Zurich), and Yannick Zakowski (ENS Rennes). He was an examiner for the PhD thesis of Zeinab Bakhtiarinoodeh (Univ. de Lorraine) and the habilitation of Alain Giorgetti (Univ. de Bourgogne et Franche Comté).

10.3. Science outreach

Marie Duflot-Kremer took part in various science outreach activities, with a public ranging from primary school kids to teachers and potential university students. A selection of these activities is given below.

General activities.

She is responsible for the scientific part of the fifth and last module in the Class'Code project (supervising a programming project from scratch), aiming at training teachers and educators for carrying out computer science activities with childrens aged 8 to 14 years.

Three days at “Fête de la Science” in Nancy (Faculté des Sciences et Technologies) and at Cité des Sciences, Paris, including a visit of the Minister of Higher Education and Research, Frédérique Vidal.

She is a member of the steering committee of an itinerant exhibition, intended for explaining computer science to the public, and that had its opening in early 2017.

She co-organized the SCRATCH17BDX international conference on Scratch and creative programming for kids in Bordeaux.

Activities for teachers/trainers.

She is a member of three working groups (unplugged activities, programming in secondary school and in high school) including university and secondary school teachers, dedicated to the training of math teachers. Two days of training on unplugged computer science activities were given to secondary and high school teachers.

A training session for kindergarden teachers to include in their “school project” unplugged activities related to programming for kids from 3 to 6 years old.

Several activities for the “ISN day”, aimed at high school teachers teaching computer science courses.

A publication (post proceedings to appear in 2018) was accepted at the COPIRELEM colloquium, aimed at math trainers for primary school teachers.

Activities for students/pupils.

Several activities for school kids from 6 to 10 years old at Ecole Marcel Leroy, Nancy.

She was involved in the *Math en Jeans* project where secondary school kids discover what doing research means.

Various outreach activities (related to data bases, model checking, algorithms etc.) during two days aimed at presenting the university to high school students.

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