



RESEARCH CENTER
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FIELD

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Section Scientific Foundations

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ALICE Project-Team

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 hundreds of 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 [25]. 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 hundreds of 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.*, [26]). 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 hundreds of millions of 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 [15]. 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 [24]. 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 [19]. 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 [16].

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 [22]. We also showed the applicability of this method, by proposing the first algorithm that converts a scanned mesh into a Spline surface automatically [18].

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 [23] or inside volumes [14] [17].

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.

BIGS Project-Team

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 [89], [66]. Piecewise deterministic processes are non diffusion processes also frequently used in the biological context [56], [65], [58]. Among Markov model, we developed strong expertise about processes derived from Brownian motion and Stochastic Differential Equations [81], [64]. For instance, knowledge about Brownian or random walk excursions [88], [80] helps to analyse genetic sequences and to develop inference about it. However, nature provides us with many examples of systems such that the observed signal has a given Hölder regularity, which does not correspond to the one we might expect from a system driven by ordinary Brownian motion. This situation is commonly handled by noisy equations driven by Gaussian processes such as fractional Brownian motion or fractional fields. The basic aspects of these differential equations are now well understood, mainly thanks to the so-called rough paths tools [72], but also invoking the Russo-Vallois integration techniques [82]. The specific issue of Volterra equations driven by fractional Brownian motion, which is central for the subdiffusion within proteins problem, is addressed in [57]. 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 [69], or for anisotropic models [53].

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 [68], [49], [55]. But, the inference problem for diffusions driven by a fractional Brownian motion is still in its infancy. Our team has a good expertise about inference of the jump rate and the kernel of Piecewise Deterministic Markov Processes (PDMP) [45], [46], [44], [47]. 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". As an example, in 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 [50], and we also used mixed models to estimate tumor growth [51].

We consider the control of stochastic processes within the framework of Markov Decision Processes [79] 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 [52]. Regarding complexity, a central topic of research is the analysis of the Policy Iteration algorithm, which has made significant progress in the last years [91], [78], [63], [87], 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 [85], [84], [86], [71], [83], 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. [90] 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 [90], [73], [61], [62]. 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 and 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 [77], [67]. Among them we have developed nonparametric estimation by local analysis via kernel methods [59], [60] 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 [70], which allows one to approximate eigenvectors in a stepwise manner [76], [74], [75]. BIGS aims at performing accurate classification or clustering by taking advantage of the possibility of updating the information "online" using stochastic approximation algorithms [54]. 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.

CAMUS Team

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 software and the new multicore processors evolution. They also correspond to the main research directions suggested by Hall, Padua and Pingali in [27]. Performance, correctness 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 actual 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 addresses, 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.

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, the complexity of current and future architectures 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 correctness 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.

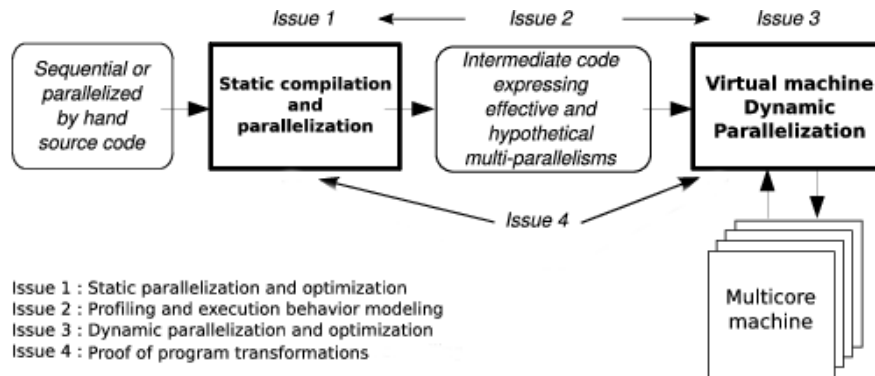


Figure 1. Automatic parallelizing steps for multicore architectures

Static optimizations, from source code at compile time, benefit from two decades of research in automatic parallelization: many works address the parallelization of loop nests accessing multi-dimensional arrays, and these works are now mature enough to generate efficient parallel code [23]. Low-level optimizations, in the assembly code generated by the compiler, have also been extensively dealt with 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, Salwa Kobeissi.

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: Philippe Clauss, Salwa Kobeissi, Jens Gustedt, Alain Ketterlin, Muthena Abdul Wahab, Mariem Saied, Daniel Salas, Maxime Mogé.

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 controlling the complexity of those new mechanisms. 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 the evolution of the availability of live resources.

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 [28]. Proving transformations involving program which are not data-race free will constitute a longer term research goal.

CAPSID Project-Team

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 [85], [57]. 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 [61], [90]. Therefore, developing techniques which can mine knowledge of protein structures and their interactions is an important way to enhance our knowledge of biology [42].

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 [89]. 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 [76]. 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 [64]. 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 [50], 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) [55].

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 [58] developed by the Human Genome Organization (HUGO) mostly address the experimental wet lab aspects leading to data production and curation [69]. 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 [92]. 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” [54], 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 [2], [4], 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) [86] functional annotations between standard UniProt (<http://www.uniprot.org/>) sequence identifiers and protein structures from the Protein Data Bank (PDB) [41] 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 [1]. 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 CODAC was presented at IWBBIO-2017 [36], and a full paper has recently been accepted by BMC Bioinformatics [13].

3.1.5. Protein Function Annotation

Knowledge of the functional properties of proteins can shed considerable light on how they might interact. However, huge numbers of protein sequences in public databases lack any functional annotation, and the annotation of sequences in such databases is a highly challenging problem. We are developing graph-based and machine learning techniques to annotate automatically the available unannotated sequences in such databases with functional properties such as EC numbers and Gene Ontology (GO) terms. Even if the 3D structures of proteins are unknown, it is natural to suppose that their sequences may be related to each other by the domains, domain families, and super-families that they share. In the frame of the PhD project of Bishnu Sarker, we recently developed a novel graph-based approach called GrAPFI for the automatic functional annotation of protein sequences based on these principles in order to transfer annotations from expert-reviewed sequences to unreviewed sequences in the UniProtKB databases [32], [24].

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 [77], the shape of a protein molecule is represented using polar Fourier series expansions of the form

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

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 [60]

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

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 [78]. 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 [79], [62], 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], [78]. 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 [40], [75], [84]. For example, using our operator notation (in which \hat{R} and \hat{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

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

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 [53]. Although we currently use shape-based FFT correlations, the symmetry operator technique may equally be used to build and 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 [68], [52], [65], [66]. In our experience, docking ensembles of NMA conformations does not give much improvement over basic FFT-based soft docking [87], and it is very computationally expensive to use side-chain repacking to refine candidate soft docking poses [3].

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 [39]. 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 [83]. Furthermore, this kind of coarse-graining effectively integrates out many of the internal DOFs to leave a smoother but still physically realistic energy surface [59]. 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 [31], [82].

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, it 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 [49], and secondly by using fast CG representations and knowledge-based distance restraints to prune large regions of the search space (thesis project of Maria Elisa Ruiz Echartea).

CARAMBA Project-Team

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 during 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 with 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 [30].

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 $\text{GF}(2)$) 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. Symmetric Cryptography

Since the recruiting of Marine Minier in September 2016 as a Professor at Université de Lorraine, and of Virginie Lallemand as a CNRS researcher in October 2018, 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.

3.4. 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.

3.5. 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 basis algorithms that can achieve large speedups compared to generic implementations [22], [21].

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 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 Cryptography in general. On the narrower topic of the Elliptic Curve Discrete Logarithm Problem on small characteristic finite fields, the highly structured polynomial systems that are involved match well our expertise on the topic of polynomial systems. Once a very hot topic in 2015, activity on this precise problem seems to have slowed down. Yet, the conjunction of skills that we have may lead to results in this direction in the future.
- The recent hiring of Marine 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 [22], [21]. We also want to see these recent results provide practical benefits compared to existing software, in particular for systems relevant for cryptanalysis.

Coast Project-Team

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 centralised authority based collaboration toward a decentralised collaboration. Users will have full control over their data. They can store them 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. Service oriented Computing [29] 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 is to focus on the issue of the efficient and flexible construction of reliable and secure high-level services. We aim to achieve it through the coordination/orchestration/composition of other services provided by distributed organisations 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) [34] 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 centralised, decentralised 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 promotes 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 [32] 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:

- operational transformation (OT) algorithms [23]
- algorithms based on commutative replicated data types (CRDT) [30].

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 parametrised 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 [28], 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. Many efforts have been devoted to establish standard business process models founded on well-grounded theories (e.g. Petri Nets) that meet the needs of business analysts, software engineers and software integrators. This has led 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 points of view. It resulted in the development of the Bonita Business process management system. It resulted also more recently on our work in crisis management where the same people are designing, executing and monitoring the process as it executes. More generally, and at a larger scale, we have been considering the problem of processes spanning the barriers of organisations. It leads to the more general problem of service composition as a way to coordinate inter organisational construction of applications. These applications provide value, based on the composition of lower level services [20].

3.5. Service Composition

We are considering processes as pieces of software whose execution traverses 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. We try to find the best compromise between the need for privacy of internal processes from organisations and the necessity to publicise large part of them. To do that, we propose to distribute the execution and the orchestration of processes among the organisations themselves, and attempting to ensure non-functional properties in this distributed setting [19]. Non-functional aspects of service composition relate to all the properties and service agreements that one wants to ensure. They are orthogonal to the actual business but they 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 some properties (e.g. transactional properties) during process execution, either by design or by the definition of some protocols. We also extended our work to the problems of security, privacy and service level agreement among partners. Recently, we started a study on service composition for software architects where services are coming from different providers with different plans (capacity, degree of resilience...). The objective is to support the architects to select the most accurate services (wrt. to their requirements, both functional and non-functional) and plans for building their software. We also compute the properties that we enforce for the composition of these services.

GAMBLE Project-Team

3. Research Program

3.1. Non-linear computational geometry



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 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 a loss of accuracy which is sometimes not an issue but which can also be most problematic depending on the application. In addition, discretization 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 [\[42\]](#), [\[43\]](#), [\[44\]](#), [\[46\]](#), [\[51\]](#)). 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 [\[29\]](#), [\[30\]](#), [\[52\]](#).

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 in its infancy. And it should be stressed that these two sets of results were not anecdotal but flagship results produced during the lifetime of the 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 intersection⁰ which was used by researchers in, for instance, photochemistry, computer vision, statistics and mathematics.

3.2. Non-Euclidean computational geometry



Figure 2. Left: 3D mesh of a gyroid (triplly periodic surface) [54]. Right: Simulation of a periodic Delaunay triangulation of the hyperbolic plane [24].

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 Aurenhammer *et al.* [23]). Some members of GAMBLE have been contributing to these algorithmic advances (see, e.g. [28], [62], [39], [27]); 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 domains⁰ 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 [34]. This work has already yielded a fruitful collaboration with astrophysicists [47], [63] and new collaborations with physicists are emerging. To the best of our knowledge, our CGAL package [33] 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 [35]. As far as non-compact manifolds are concerned, past approaches, limited to the two-dimensional case, have stayed theoretical [53].

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 [32].

⁰QI: <http://vegas.loria.fr/qi/>.

⁰<http://www.cgal.org/>

⁰See <http://www.cgal.org/projects.html> for details.

⁰See <http://www.loria.fr/~teillaud/PeriodicSpacesWorkshop/>, <http://www.lorentzcenter.nl/lc/web/2009/357/info.php3?wsid=357>,

<http://neg15.loria.fr/> and <http://gerdschroeder-turk.org/2015/06/17/shape-up-2015-exercises-in-materials-geometry-and-topology/>.

⁰See examples at <http://www.cgal.org/projects.html>

Moreover, while our solution for computing triangulations in hyperbolic spaces can be considered as ultimate [24], 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 [55], neuromathematics [37], or physics [58]. Even the simplest possible case (a surface homeomorphic to the torus with two handles) shows strong mathematical difficulties [25], [60].

3.3. Probability in computational geometry

In most computational geometry papers, algorithms are analyzed in the worst-case setting. This often yields too pessimistic complexities that arise only in pathological situations that are unlikely to occur in practice. On the other hand, probabilistic geometry provides analyses with great precision [56], [57], [31], but using hypotheses with much more randomness than in most realistic situations. We are developing new algorithmic designs improving state-of-the-art performance 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 [61] (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 [38] and we only obtained in 2015 breakthrough results, but still not definitive [41], [40], [45].

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” [21] 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-offs between full randomness and worst case may also appear in other forms such as dependent distributions, or random distributions conditioned to be in some special configurations. Simulating these kinds of geometric distributions is currently out of reach for more than a few hundred points [48] although it has practical applications in physics or networks.

LARSEN Project-Team

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 [34], [42]. 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 [34], [40].

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 [39].

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 [33] 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 [48], [40]. However, current reinforcement learning algorithms require hundreds of trials/episodes to learn a single, often simplified, task [40], 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 [41], [1].

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 [38]. 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 [46], [38], [32]).

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 [51]. Most Human-Robot Interaction (HRI) studies focus on verbal communication [47] 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 [49] and robotic co-workers [44]. 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 [35].

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) [50] is an approach 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/her possible future positions (especially in the case of occlusions). This direction has been tested with simulator and particle filters [37], and one promising direction would be to couple STAR with decision making formalisms like partially observable Markov decision processes (POMDPs). This would allow us 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

should 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 [36]. This will be tackled through different techniques, going from Bayesian state estimation (particle filtering), to learning, active and distributed sensing.

MAGRIT Project-Team

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 [2].

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.

MFX Team

3. Research Program

3.1. Research Program

We focus on the computational aspects of shape modeling and processing for digital fabrication. A particular emphasis is on dealing with shape complexity, revisiting design and customization of existing parts in view of novel possibilities afforded by AM, and providing a stronger integration between modeling and the capabilities of the target processes.

Specifically, we focus on the following challenges:

- develop **novel shape synthesis and shape completion algorithms** that can help users model shapes with features in the scale of microns to meters, while following functional, structural, geometric and fabrication requirements;
- propose methodologies to help *expert* designers **describe shapes** and designs that can be **later customized and adapted** to different use cases;
- develop novel algorithms to **adapt and prepare complex designs** for fabrication in a given technology, including the possibility to modify aspects of the design while preserving its functionality;
- develop novel techniques to **unlock the full potential of fabrication processes**, improving their versatility in terms of feasible shapes as well as their capabilities in terms of accuracy and quality of deposition;
- develop **novel shape representations, data-structures, visualization and interaction techniques** to support the integration of our approaches into a single, unified software framework that covers the full chain from modeling to printing instructions;
- **integrate novel capabilities** enabled by advances in additive manufacturing processes and materials **in the modeling and processing chains**, in particular regarding the use of functional materials (*e.g.* piezoelectric, conductive, shrinkable).

Our approach is to cast a holistic view on the aforementioned challenges, by considering modeling and fabrication as a single, unified process. Thus, the modeling techniques we seek to develop will take into account the geometric constraints imposed by the manufacturing processes (minimal thickness, overhang angles, trapped material) as well as the desired object functionality (rigidity, porosity). To allow for the modeling of complex shapes, and to adapt the same initial design to different technologies, we propose to develop techniques that can automatically synthesize functional details within parts. At the same time, we will explore ways to increase the versatility of the manufacturing processes, through algorithms that are capable of exploiting additional degrees of freedom (*e.g.*, curved layering [11]), can introduce new capabilities (*e.g.*, material mixing [20]) and improve part accuracy (*e.g.*, adaptive slicing [18]).

Our research program is organized along three main research directions. The first one focuses on the automatic synthesis of shapes with intricate, multi-scale geometries, in the context of additive manufacturing. The second direction considers geometric and algorithmic techniques for the actual fabrication of the modeled object, further improving the capabilities of the manufacturing processes by producing improved deposition strategies. The third direction focuses on computational design algorithms to help model parts with gradient of properties, as well as to help customizing existing complex parts for their reuse.

These three research directions interact strongly, and cross-pollinate: *e.g.*, novel possibilities in manufacturing unlock novel possibilities in terms of shapes that can be synthesized. Stronger synthesis methods allow for further customization.

MIMESIS Team

3. Research Program

3.1. Real Time Patient-Specific Computational Models

The principal objective of this challenge is to improve, at the numerical level, the efficiency, robustness, and quality of the simulations (see Fig. 2). To reach these goals, we will investigate novel finite element techniques able to cope with complex, potentially ill-defined input data. After developing Smoothed FEM for real-time simulations, we are developing meshless techniques and immersed boundary methods. The first one is also well suited for topological changes, which we sometimes need to account for in our simulations. The second is expected to lead to more stable, and numerically efficient, formulations of the finite element method.

We will also propose numerical techniques such as domain decomposition and model order reduction, to handle real-time computation on more complex geometries or constitutive models. Boundary conditions are known to also play an important role in the solution of such problems. Therefore we are developing solutions to both identify and model the interactions that take place between the structure of interest and its anatomical environment.

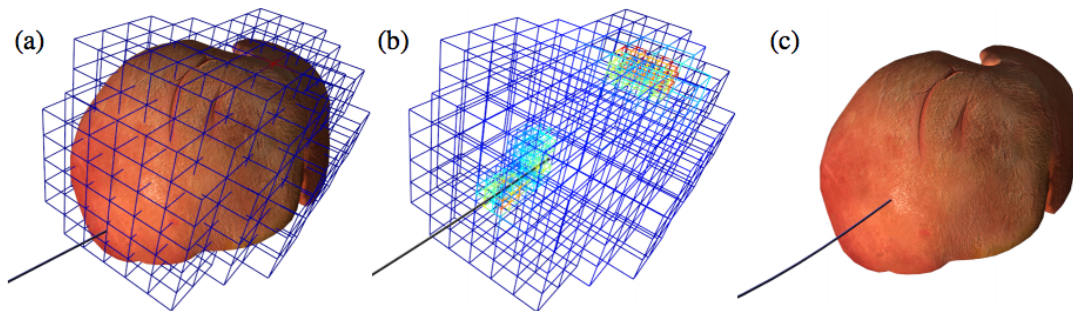


Figure 2. (a) Simulation of needle insertion in a liver; (b) Using dynamic mesh refinement scheme driven by error estimate; (c) Visual depiction. The simulation runs at 22 Hz using a PC with 4 GHz CPU.

3.2. Data-driven Simulation

Data-driven simulation has been a recent area of research in our team (see Fig. 3). We have demonstrated that it has the potential to bridge the gap between medical imaging and clinical routine by adapting pre-operative data to the time of the procedure. In the areas of non-rigid registration and augmented reality during surgery, we have demonstrated the benefit of our physics-based approaches with several key publications in major conferences (MICCAI, CVPR, IPCAI) and awards (best paper [25] at ISMAR 2013, second best paper [26] at IPCAI 2014).

We have continued this work with an **emphasis on robustness to uncertainty and outliers** in the information extracted in real-time from image data, as well as real-time parameter estimation. This is currently done by **combining Bayesian methods with advanced physics-based methods** to handle uncertainties in image-driven simulations (MICCAI 2017, CVCS 2018).

Finally, Bayesian or similar methods require to perform a large amount of simulations to sample the domain space, even when using efficient methods such as Reduced Order Unscented Kalman Filters. For this reason, we are investigating the use of neural networks to perform predictions instead of using full numerical simulations. Our latest paper [5] at MICCAI 2018 shows it is possible to **teach a neural network from numerical simulations** and **predict, with high accuracy, the relationship between an image of the anatomy and the associated force**.

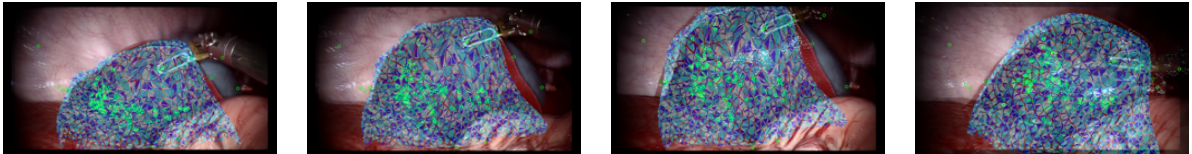


Figure 3. Real-time deformation of a virtual liver according to tissue motion tracked in laparoscopic images.

MOCQUA Team

3. Research Program

3.1. Quantum Computing

While it can be argued that the quantum revolution has already happened in cryptography [35] or in optics [34], quantum computers are far from becoming a common commodity, with only a few teams around the world working on a practical implementation. In fact, one of the most commonly known examples of a quantum computer, the D-Wave 2X System, defies the usual definition of a computer: it is not general-purpose, and can only solve (approximately) a very specific hardwired problem.

Most current prototypes of a quantum computer differ fundamentally on the hardware substrate, and it is quite hard to predict which solution will finally be adopted. The landscape of quantum programming languages is also constantly evolving. Comparably to compiler design, the foundation of quantum software therefore relies on an intermediate representation that is suitable for manipulation, easy to produce from software and easily encodable into hardware. The language of choice for this is the ZX-calculus.

Regardless of the actual model that will be accepted by the industry, it is becoming clear that some of the hurdles into scaling up quantum computers from a few qubits to very large arrays will remain. As an example, current implementations of quantum computers working on hundreds of qubits indeed are not able to form and maintain all possible forms of entanglement between qubits. This raises two questions. First, does this restrict the computational power, and the supposed advantage of the quantum computer over the classical computer? Second, how to ensure that a quantum program that was designed for a theoretical quantum computer will work on the practical implementations? This will be investigated, in particular by providing static analysis methods for evaluating a priori how much entanglement a quantum program needs.

3.2. Higher-Order Computing

While programs often operate on natural numbers or finite structures such as graphs or finite strings, they can also take functions as input. In that case, the program is said to perform higher-order computations, or to compute a higher-order functional. Functional programming or object-oriented programming are important paradigms allowing higher-order computations.

While the theory of computation is well developed for first-order programs, difficulties arise when dealing with higher-order programs. There are many non-equivalent ways of presenting inputs to such programs: an input function can be presented as a black-box, encoded in an infinite binary sequence, or sometimes by a finite description. Comparing those representations is an important problem. A particularly useful application of higher-order computations is to compute with infinite objects that can be represented by functions or symbolic sequences. The theory works well in many cases (to be precise, when these objects live in a topological space with a countable basis [40]), but is not well understood in other interesting cases. For instance, when the inputs are the second-order functionals (of type $(\mathbb{N} \rightarrow \mathbb{N}) \rightarrow (\mathbb{N} \rightarrow \mathbb{N})$), the classical theory does not apply and many problems are still open.

3.3. Dynamical Systems

The most natural example of a computation with infinite precision is the simulation of a dynamical system. The underlying space might be \mathbb{R}^n in the case of the simulation of physical systems, or the Cantor space $\{0, 1\}^{\mathbb{Z}}$ in the case of discrete dynamical systems.

From the point of view of computation, the main point of interest is the link between the long-term behavior of a system and its initial configuration. There are two questions here: (a) predict the behavior, (b) design dynamical systems with some prescribed behavior. The first will be mainly examined through the angle of reachability and more generally control theory for hybrid systems.

The model of cellular automata will be of particular interest. This computational model is relevant for simulating complex global phenomena which emerge from simple interactions between simple components. It is widely used in various natural sciences (physics, biology, etc.) and in computer science, as it is an appropriate model to reason about errors that occur in systems with a great number of components.

The simulation of a physical dynamical system on a computer is made difficult by various aspects. First, the parameters of the dynamical systems are seldom exactly known. Secondly, the simulation is usually non exact: real numbers are usually represented by floating-point numbers, and simulations of cellular automata only simulate the behavior of finite or periodic configurations. For some chaotic systems, this means that the simulation can be completely irrelevant.

MULTISPEECH Project-Team

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. 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. 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. 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).

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 aim is to provide 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, 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 machine learning-based approaches for handling 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 (thus going beyond the few preceding words of the n -gram models) and evolutive lexicons necessary when dealing with diachronic audio documents. With respect to the generation of speech signals, MULTISPEECH considers parametric 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, speech recognition performance depends on the quality of the input speech signals, and performance degrades quickly with noisy or reverberated 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 on 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, one difficulty is to design scalable estimation algorithms robust to overfitting, to integrate them into the recently developed FASST [6] and KAM software frameworks if relevant, and to develop new software frameworks otherwise.

3.2.2. Ambient sounds detection and classification

We are constantly surrounded by a complex audio stream carrying information about our environment. Hearing is a privileged way to detect and identify events that may require quick action (ambulance siren, baby cries...). Indeed, audition offers several advantages compared to vision: it allows for omnidirectional detection, up to a few tens of meters and independently of the lighting conditions. For these reasons, automatic audio analysis has become increasingly popular over the past few years. Yet, machines are still limited to detecting and classifying a few tens of sound event classes while human can generally recognize a few thousand. Besides, current algorithms rely heavily on the availability of annotated data that are extremely costly to obtain. In MULTISPEECH we focus on developing new methods, independent of applications, that would enable the detection of thousands of audio events from a little amount of annotated data while being robust to “out-of-the lab” conditions.

3.2.3. 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, for which utterances are often ill-formed and frequently contain disfluencies (hesitations, repetitions, ...) that degrade speech recognition performance, and pronunciation lexicons which are critical especially when dealing with non-native speech and foreign names.

3.2.4. Speaker identification

Speaker identification is the task that consists in identifying a person based on a voice recording. It has recently been deployed in several real-world application including secured access to bank services via telephone or internet. However, identification based solely on voice remains a modality with limited reliability under real conditions including several acoustic perturbations (noise, reverberation...) when the speaker might not be cooperative (a limited amount of data is available). In MULTISPEECH we focus on exploring new approaches exploiting multichannel speech enhancement techniques and uncertainty propagation to improve the performance of speaker identification systems in real conditions and with short speech utterances.

3.2.5. Speech generation by statistical methods

Over the last few years parametric speech synthesis has emerged as an alternative to corpus-based speech synthesis. The announced advantages of the parametric 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). MULTISPEECH investigates parametric approaches (currently based on deep learning) to produce expressive audio-visual speech. Also, in the context of acoustic feedback in foreign language learning, voice modification approaches are studied 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 the goal of estimating the reliability and/or the uncertainty on 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. 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. 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 need to 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 plans to investigate the combination of several speech-text alignments as a way of improving the quality of speech-text alignment and of getting information on the reliability of the phonetic boundaries. When segmenting speech corpora, knowing the reliability of the boundaries will help deciding which parts of the corpora need to be manually checked and corrected, thus avoiding 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 aims at estimating the uncertainty of the duration of the phones (see uncertainty of phonetic boundaries above) and of the fundamental frequency estimates, 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.

NEUROSYS Project-Team

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

Models implementation 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 powerful 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.

ORPAILLEUR Project-Team

3. Research Program

3.1. Hybrid and Exploratory Knowledge Discovery

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 [74]) and extensions of FCA such as Pattern Structures [79] and Relational Concept Analysis (RCA [84]). Numerical methods are based on Random Forests, SVM, Neural Networks, and probabilistic approaches such as second-order Hidden Markov Models (HMM [80]).

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 [74] (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 [86].

For being able to deal with complex and large data, numerical data mining methods can be associated with symbolic methods, for improving applicability and efficiency of knowledge discovery. This is particularly true in classification, where supervised and unsupervised approaches may be combined with benefits [77].

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 knowledge discovery 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 numerical and symbolic data mining methods. 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 algorithms based on FCA and Redescription Mining which allow data exploration as well as the discovery of definition (bidirectional implication rules).

PESTO Project-Team

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 must 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 [57].

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. [56]. 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 and anonymity properties may be modelled as particular observational equivalences in process calculi [52], 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 state explosion problems. For instance, the use of Horn clause resolution techniques requires dedicated resolution methods [46][3]. Another example is unification modulo equational theory, which is a key technique in several tools, e.g. [55]. 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 [50], which is used in several tools, e.g., *Akiss* [3], Maude-NPA [55] and Tamarin [58]. Another example is the notion of asymmetric unification [54] 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 a notion of *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 finding 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 [51], [49]. 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 the 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 the study of 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 [48], [53] witnesses the need for new protocols in this area.
- Election systems that provide strong security guarantees. We have been working (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.

RESIST Team

3. Research Program

3.1. Overview

The Resist project aims at designing, implementing and validating novel models, algorithms and tools to **make networked systems elastic and resilient so as to enhance their scalability and security**, assuming users, applications and devices whose volume and heterogeneity will continue to increase.

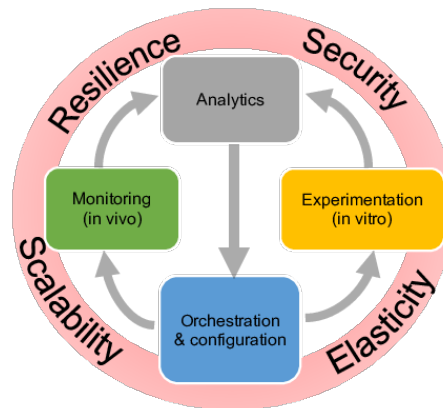


Figure 1. The Resist project

Softwarization of networks and **data analytics** are key enablers to design intelligent methods to orchestrate – *i.e.* configure in a synchronized and distributed manner – both network and system resources. Intelligent **orchestration** leverages relevant data for decision-making using **data analytics**. Input data reflecting the past, current and even future (predicted) states of the system are used to build relevant knowledge. Two approaches are pursued to generate knowledge and to validate orchestration decisions. First, a running system can be **monitored in vivo**. Second, **in vitro experimentation** in a controlled environment (simulators, emulators and experimental platforms) is helpful to reproduce a running system with a high reliability and under different hypotheses. Monitoring and experimentation are steered and configured through orchestration according to the two intertwined loops illustrated in Figure 1 .

Accordingly Resist is thus structured into four main research objectives (activities) namely Monitoring, Experimentation, Analytics and Orchestration.

3.2. Monitoring

The evolving nature of the Internet ecosystem and its continuous growth in size and heterogeneity call for a better understanding of its characteristics, limitations, and dynamics, both locally and globally so as to improve application and protocol design, detect and correct anomalous behaviors, and guarantee performance.

To face these scalability issues, **appropriate monitoring models, methods and algorithms are required for data collection, analysis and sharing** from which knowledge about Internet traffic and usage can be extracted. Measuring and collecting traces necessitate user-centered and data-driven paradigms to cover the wide scope of heterogeneous user activities and perceptions. In this perspective, we propose monitoring algorithms and architectures for large scale environments involving mobile and Internet of Things (IoT) devices.

Resist also assesses **the impact of the Internet infrastructure evolution integrating network softwarization on monitoring**, for example the need for dedicated measurement methodologies. We take into account not only the technological specifics of such paradigms for their monitoring but also the ability to use them for collecting, storing and processing monitoring data in an accurate and cost-effective manner.

Crowd-sourcing and third-party involvement are gaining in popularity, paving the way for massively distributed and collaborative monitoring. We thus investigate opportunistic mobile crowdsensing in order to collect user activity logs along with contextual information (social, demographic, professional) to effectively measure end-users' **Quality of Experience**. However, collaborative monitoring raises serious concerns regarding trust and sensitive data sharing (open data). Data anonymization and sanitization need to be carefully addressed.

3.3. Experimentation

Of paramount importance in our target research context is experimental validation using testbeds, simulators and emulators. In addition to using various existing experimentation methodologies, Resist contributes in **advancing the state of the art in experimentation methods and experimental research practices**, particularly focusing on elasticity and resilience.

We develop and deploy testbeds and emulators for **experimentation with new networking paradigms** such as SDN and NFV, to enable large-scale in-vitro experiments combining all aspects of Software-Defined Infrastructures (server virtualization, SDN/NFV, storage). Such fully controlled environments are particularly suitable for our experiments on resilience, as they ease the management of fault injection features.

We are playing a central role in the development of the Grid'5000 testbed [34] and our objective is to reinforce our collaborations with other testbeds, towards a **testbed federation** in order to enable experiments to scale to multiple testbeds, providing a diverse environment reflecting the Internet itself.

Moreover, our research focuses on extending the infrastructure virtualization capabilities of our Distem [37] emulator, which provides a flexible software-based experimental environment.

Finally, methodological aspects are also important for ensuring **trustworthy and reproducible experiments**, and raises many challenges regarding testbed design, experiment description and orchestration, along with automated or assisted provenance data collection [35].

3.4. Analytics

A large volume of data is processed as part of the operations and management of networked systems. These include traditional monitoring data generated by network components and components' configuration data, but also data generated by dedicated network and system probes.

Understanding and predicting security incidents or system ability to scale requires the elaboration of novel **data analytics techniques** capable to cope with large volumes of data generated from various sources, in various formats, possibly incomplete, non-fully described or even encrypted.

We use machine learning techniques (*e.g.* Topological Data Analysis or multilayer perceptrons) and leverage our domain knowledge to fine-tune them. For instance, machine learning on network data requires the definition of new distance metrics capable to capture the properties of network configurations, packets and flows similarly to edge detection in image processing. Resist contributes to developing and making publicly available an **analytics framework dedicated to networked systems** to support Intelligence-Defined Networked Systems.

Specifically, the goal of the Resist analytics framework is to facilitate the extraction of knowledge useful for **detecting, classifying or predicting security or scalability issues**. The extracted knowledge is then leveraged for orchestration purposes to achieve system elasticity and guarantee its resilience. Indeed, predicting when, where and how issues will occur is very helpful in deciding the provisioning of resources at the right time and place. Resource provisioning can be done either reactively to solve the issues or proactively to prepare the networked system for absorbing the incident (resiliency) in a timely manner thanks to its elasticity.

While the current trend is towards centralization where the collected data is exported to the cloud for processing, we seek to extend this model by also developing and evaluating novel approaches in which **data analytics is seamlessly embedded within the monitored systems**. This combination of big data analytics with network softwarization enablers (SDN, NFV) can enhance the scalability of the monitoring and analytics infrastructure.

3.5. Orchestration

The ongoing transformations in the Internet ecosystem including network softwarization and cloudification bring new management challenges in terms of service and resource orchestration. Indeed, the growing sophistication of Internet applications and the complexity of services deployed to support them require novel models, architectures and algorithms for their automated **configuration** and **provisioning**. Network applications are more and more instantiated through the **composition of services, including virtualized hardware and software resources**, that are offered by **multiple providers** and are subject to changes and updates over time. In this dynamic context, efficient orchestration becomes fundamental for ensuring performance, resilience and security of such applications. We are investigating the chaining of different functions for supporting the security protection of smart devices, based on the networking behavior of their applications.

From a resilience viewpoint, this orchestration at the network level allows the dynamic **reconfiguration of resources** to absorb the effects of congestions, such as link-flooding behaviors. The goal is to drastically reduce the effects of these congestions by imposing dynamic policies on all traffic where the network will adapt itself until it reaches a stable state. We also explore mechanisms for **detecting and remediating potential dysfunctions** within a virtualized network. Corrective operations can be performed through dynamically composed VNFs (Virtualized Network Functions) based on available resources, their dependencies (horizontal and vertical), and target service constraints. We also conduct research on verification methods for automatically assessing and validating the composed chains.

From a security viewpoint, this orchestration provides **prevention mechanisms** that capture adversaries' intentions early and **enforces security policies** in advance through the available resources, to be able to proactively mitigate their attacks. We mainly rely on the results obtained in our research activity on security analytics to build such policies, and the orchestration part focuses on the required algorithms and methods for their automation.

SEMAGRAMME Project-Team

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 [47], 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).

SPHINX Project-Team

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 [95], [90], [72], 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** ([55], [51], [89], [61], [66], [92], [94], [79], [64]). Many other FSIS have been studied as well. Let us mention [81], [69], [65], [54], [44], [60], [45], [62] 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: [49], [44], [75], [56], [47]). Without approximations, the only known results [52], [53] 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 ([87]). 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 [70], [46], [83].

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 [71] or Kaltenbacher, Neubauer, and Scherzer [73]). 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 [39], [63], [67], [91] for the design of feedback controllers), an input (for instance source inverse problems [36], [48], [57]) 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 ([50]), specific one-dimensional techniques (like in [40]) or observer-based methods as in [77].

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 [76], 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 [80] or [93]). Using observers, we have proposed in [82], [68] 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 [42], [41].

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 Dirichlet-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. [86], [74], [88], [84], [85], [78]).
- **Simulation of CWS:** Solving acoustic or electromagnetic scattering problems can become a tremendously hard task in some specific situations. In the high frequency regime (i.e. for small wavelength), acoustic (Helmholtz's equation) or electromagnetic (Maxwell's equations) scattering problems are known to be difficult to solve while being crucial for industrial applications (e.g. in aeronautics and aerospace engineering). Our particularity is to develop new numerical methods based on the hybridization of standard numerical techniques (like algebraic preconditioners, etc.) with approaches borrowed from asymptotic microlocal analysis. Most particularly, we contribute to building hybrid algebraic/analytical preconditioners and quasi-optimal Domain Decomposition Methods (DDM) [43], [58], [59] 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 interactions 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 [38], [37]), 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.

TONUS Team

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.

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 computation. 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. [22]) 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. [21].

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) [26] for the simulation of core turbulence that has been developed at CEA Cadarache in collaboration with our team [23].

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 [10]. 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 [20].

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 MagnetoHydro-Dynamic (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 [1].

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 [27], [19], [25], [24].

3.2.2. Matrix-free Implicit schemes

In tokamaks, the reduced model generally involves many time scales. Among these time scales, many of them, 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 [1].

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 [17] (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.

TOSCA Project-Team

3. Research Program

3.1. Research Program

Most often physicists, economists, biologists and engineers need a stochastic model because they cannot describe the physical, economical, biological, etc., experiment under consideration with deterministic systems, either because of its complexity and/or its dimension or because precise measurements are impossible. Therefore, they abandon trying to get the exact description of the state of the system at future times given its initial conditions, and try instead to get a statistical description of the evolution of the system. For example, they desire to compute occurrence probabilities for critical events such as the overstepping of a given thresholds by financial losses or neuronal electrical potentials, or to compute the mean value of the time of occurrence of interesting events such as the fragmentation to a very small size of a large proportion of a given population of particles. By nature such problems lead to complex modelling issues: one has to choose appropriate stochastic models, which require a thorough knowledge of their qualitative properties, and then one has to calibrate them, which requires specific statistical methods to face the lack of data or the inaccuracy of these data. In addition, having chosen a family of models and computed the desired statistics, one has to evaluate the sensitivity of the results to the unavoidable model specifications. The TOSCA team, in collaboration with specialists of the relevant fields, develops theoretical studies of stochastic models, calibration procedures, and sensitivity analysis methods.

In view of the complexity of the experiments, and thus of the stochastic models, one cannot expect to use closed form solutions of simple equations in order to compute the desired statistics. Often one even has no other representation than the probabilistic definition (e.g., this is the case when one is interested in the quantiles of the probability law of the possible losses of financial portfolios). Consequently the practitioners need Monte Carlo methods combined with simulations of stochastic models. As the models cannot be simulated exactly, they also need approximation methods which can be efficiently used on computers. The TOSCA team develops mathematical studies and numerical experiments in order to determine the global accuracy and the global efficiency of such algorithms.

The simulation of stochastic processes is not motivated by stochastic models only. The stochastic differential calculus allows one to represent solutions of certain deterministic partial differential equations in terms of probability distributions of functionals of appropriate stochastic processes. For example, elliptic and parabolic linear equations are related to classical stochastic differential equations (SDEs), whereas nonlinear equations such as the Burgers and the Navier–Stokes equations are related to McKean stochastic differential equations describing the asymptotic behavior of stochastic particle systems. In view of such probabilistic representations one can get numerical approximations by using discretization methods of the stochastic differential systems under consideration. These methods may be more efficient than deterministic methods when the space dimension of the PDE is large or when the viscosity is small. The TOSCA team develops new probabilistic representations in order to propose probabilistic numerical methods for equations such as conservation law equations, kinetic equations, and nonlinear Fokker–Planck equations.

VERIDIS Project-Team

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 the SPASS [10] **workbench**. It currently consists of one of the leading automated theorem provers for first-order logic based on the superposition calculus [51] and a theory solver for linear arithmetic.

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 SMT⁰ solver that combines decision procedures for different fragments of 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 difficult or impossible to express 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⁺ [67] 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.

⁰Satisfiability Modulo Theories [54]

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], [52], [68] in state-based modeling formalisms is central to our approach because it allows us to present a rational (re)construction of system development. An important goal in designing such methods is to establish precise proof obligations many of which can be discharged by automatic tools. This requires taking into account specific characteristics of certain classes of systems and tailoring the model to concrete computational models. Our research in this area is supported by carrying out case studies for academic and industrial developments. This activity benefits from and influences the development of our proof tools.

In this line of work, we investigate specific development and verification patterns for particular classes of algorithms, in order to reduce the work associated with their verification. We are also interested in applications of formal methods and their associated tools to the development of systems that underlie specific certification requirements in the sense of, e.g., Common Criteria. Finally, we are interested in the adaptation of model checking techniques for verifying actual distributed programs, rather than high-level models.

Today, the formal verification of a new algorithm is typically the subject of a PhD thesis, if it is addressed at all. This situation is not sustainable given the move towards more and more parallelism in mainstream systems: algorithm developers and system designers must be able to productively use verification tools for validating their algorithms and implementations. On a high level, the goal of VeriDis is to make formal verification standard practice for the development of distributed algorithms and systems, just as symbolic model checking has become commonplace in the development of embedded systems and as security analysis for cryptographic protocols is becoming standard practice today. Although the fundamental problems in distributed programming are well-known, they pose new challenges in the context of modern system paradigms, including ad-hoc and overlay networks or peer-to-peer systems, and they must be integrated for concrete applications.