Activity Report 2011

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BACCHUS Team

4. Application Domains

4.1. Panorama

The main objective of the BACCHUS project is to analyze and solve scientific computing problems coming from complex research and industrial applications that require a scalable approach. This allows us to validate the numerical schemes, the algorithms and the associated software that we develop. We have today three reference application domains which are fluid mechanics, material physics and the MHD simulation dedicated to the ITER project.

In these three domains, we study and simulate phenomena that are by nature multiscale and multiphysics, and which require enormous computing power. A major part of these works leads to industrial collaborations in particular with the CNES, ONERA, and with the french CEA/CESTA, CEA/Ile-de-France and CEA/Cadarache centers.

4.2. Fluid mechanics

Participants: Rémi Abgrall [Corresponding member], Marc Duruflé, Mario Ricchiuto, Pietro Marco Congedo, Cécile Dobrzynzki, Héloïse Beaugendre, Sébastien Blaise.

The numerical simulation of steady and unsteady flows is still a challenge due to the large margin of improvement in efficiency and accuracy of the underlying numerical schemes, and of their computer implementation. The challenge is even greater when considering real applications involving complex geometries and large irregular unstructured grids. The numerical schemes developed in BACCHUS are implemented using Scotch, HIPS and PaStiX whenever the type of problems and the CPU requirements make this useful.

4.2.1. Steady transonic and supersonic flows

One of our application fields is the one of steady subsonic, transonic and supersonic flow problems when the equation of state is for example the one of air in standard conditions, or a more general one as in real gases and multiphase flows. This class of physical problems corresponds to “standard” aerodynamics and the models are those of the Euler equations and the Navier Stokes ones, possibly with turbulent effects. Here we consider residual distribution and SUPG schemes.

4.2.2. Unsteady transonic and supersonic flows

Another field of application is the one of unsteady problems for the same physical models. Depending on the applications, the physical models considered involve the Navier-Stokes equations, or the non-linear or linearized Euler equations. The schemes we develop are the Residual distribution schemes and Discontinuous Galerkin schemes. Specific modifications, with respect to their steady counter parts, are done in order to reduce dramatically the computational time, while maintaining the desired accuracy.

4.2.3. Turbulent flows

Detached-Eddy Simulation (DES) is a hybrid technique proposed by Spalart et al. in 1997 as a numerically feasible and plausibly accurate approach for predicting massively separated flows. Traditionally, high Reynolds number separated flows have been predicted using Reynolds Averaged Navier-Stokes equations (RANS). Although RANS models are considered as the most practical turbulence handling technique for industrial problems these models are not adapted to massively separated flows widely encountered when dealing with iced bodies. Another growing approach, Large-Eddy Simulation (LES), offers the advantage to directly compute the dominant unsteady structures of the flow. Unfortunately the high computational cost of applying LES to complete configurations such as an airplane, a submarine, or a road vehicle remains prohibitive because of the resolution required in the boundary layers. The aim of Detached-Eddy Simulation (DES) is to combine...
the most favourable aspects of both techniques, i.e., application of RANS models for predicting the attached
boundary layer and LES for time-dependent three-dimensional large eddies. The cost scaling of the method
is then affordable since LES is not applied to solve the relatively smaller structures that populate the bound-
ary layer. Simulations of performance degradations due to icing have increased the demand for numerically
feasible and accurate approach for predicting massively separated flows around complex geometries. In this
aspect flow field predictions obtained using DES are encouraging. To obtain the DES model formulation, the
length scale of the S-A destruction term is modified to be the minimum of the distance to the closest wall and
a length scale proportional to the local grid spacing. Concurrently with its encouraging results, weaknesses of
DES were discovered. Starting from a valid RANS solution, gradually refining the grid alters the solution in
obscure ways. The grid is ambiguous and the DES equations fail to recognize that pure RANS behaviour was
intended. Resolving the issue of ambiguous grids is a priority but as proven to be a resilient difficulty. A better
understanding of the coupling mechanisms between the models is needed.

4.2.4. Inflight icing and ice shedding

Inflight icing:
Every year, sudden aircraft performance degradation due to ice accretion causes several incidents and
accidents. Icing is a serious and not yet totally mastered meteorological hazard due to supercooled water
droplets that impact on aerodynamic surfaces. Icing results in performance degradations including substantial
reduction of engine performance and stability, reduction in maximum lift and stall angle and an increase of
drag. One of the most important challenges in understanding the performance degradation is the accurate
prediction of complex and massively separated turbulent flows. Turbulent flows are currently modelled
and computed using a variety of strategies. The majority of predictions around engineering geometries are
obtained from solutions of the Reynolds Averaged Navier-Stokes (RANS) equations. These approaches are
often acceptable in the thin shear layers where RANS methods have been calibrated. In other regimes,
especially flows in which the turbulent eddies are not standard, i.e., not in the calibration range of the model,
the performance of RANS models is, at best, uneven. This in turn motivates other strategies, one of them
being Large-Eddy Simulation (LES). The application of LES to prediction of turbulent flows in practical
configurations is increasing but the computational cost remains prohibitive. Within the past five years hybrid
methods have emerged as a popular approach for predicting complex flows. Spalart et al. proposed DES
as a cost-effective and plausibly accurate approach for predicting flows experiencing massive separation.
Therefore, the overall objectives are the following:

1. Analysis of the DES approach;
2. Develop the DES model for the simulation of 3D turbulent flow;
3. Discuss the issues that impact the method, including the underlying RANS turbulence model and the
   simulation design for DES (grids and choice of time steps);
4. Use Airbus test cases to answer the following question: is it possible and advisable to use DES to
   quantify the performance degradation due to icing;

Potential benefits:

1. Help in the certification process;
2. Include the data in flight simulators to train pilots under icing operating conditions.

Ice shedding:
Actual concerns about greenhouse gases lead to changes in the design of aircraft with an increase use of
composite materials. This in turns offers new possibilities for design of ice protection systems, thus renewing
interest in de-icing simulation tools. To save fuel burn, aircraft manufacturers are investigating ice protection
systems such as electro-thermal or electro-mechanical de-icing systems to replace anti-icing systems. By
reducing the adhesive shear strength between ice and surface, de-icing systems remove ice formed on the
protected surfaces following a periodic cycle. This cycle is defined such that inter cycle ice shapes remain
acceptable from a performance point of view. One of the drawbacks of de-icing device is the ice pieces shed
into the flow. The knowledge of ice shedding trajectories could allow assessing the risk of impact/ingestion on aircraft components located downstream. When the pieces leave the aircraft surface, they become projectiles that can hit and cause severe damage to aircraft surface or other components, such as aircraft horizontal and vertical tails, or aircraft engine. Aircraft certification authorities, such as FAA, have specific requirements for large ice fragment ingestion during engine certification. Control surfaces or wing flaps are also sensitive to ice shedding because they can be blocked by ice fragments. Aircraft manufacturers rely mainly on flight tests to evaluate the potential negative effects of ice shedding because of the lack of appropriate numerical tools. The random shape and size taken by ice shed particles together with their rotation as they move make it difficult for classical CFD tools to predict trajectories. The numerical simulation of a full unsteady viscous flow, with a set of moving bodies immersed within, shows several difficulties for grid based methods. Drawbacks income from the meshing procedure for complex geometries and the re-gridding procedure in tracing the body motion. A new approach that take into account the effect of ice accretion on flow field is used to solve the ice trajectory problem. The approach is based on mesh adaptation, penalization method and level sets.

4.2.5. Geophysical flows

A challenging and important field of application is that of free surface flows for geophysical applications such as the propagation of tsunamis, and their interaction with complex coastal environments. A model often used to simulate these phenomena is the so-called shallow water model, describing the dynamics of depth and depth averaged velocity of the water. These model, while bearing many similarities with the equations of compressible gas-dynamics, present many peculiarities: the presence of source terms modeling the effects of bathymetry variations and of friction on the bottom and often controlling the dynamics of the flow, the fact that dry states occur normally (differently from vacuum in gas-dynamics), and that their dynamics when considering wave/coast interaction is one of the most important outputs of the simulation. Our work aims at borrowing tools developed in the context of industrial/aeronautics applications for these environmental applications. In particular, we have adapted to this model the residual schemes used for aeronautic applications, showing a very important potential of this class of numerical schemes for these applications.

4.2.6. Real-gas flows in turbine cascade

An important field of application consists in the use of real-gas thermodynamic model for the simulation of turbulent flows in turbine cascade. The aim is to demonstrate the potentiality of BZT fluids for turbine applications. BZT fluids are characterized by negative values of the fundamental derivative of gasdynamics for a range of temperatures and pressures in the vapor phase, which leads to non-classical gasdynamic behaviors such as the disintegration of compression shocks. The non-classical phenomena typical of BZT fluids have several practical outcomes: prominent among them is an active research effort to reduce losses caused by wave drag and shock/boundary layer interactions in turbomachines and nozzles, with particular application to ORCs used to generate electric energy in low-power applications. The use of BZT fluids as ORC working fluids is potentially interesting because the shock formation and the consequent losses could be ideally avoided if turbine expansion could happen entirely within or very close to particular region called inversion zone where the fundamental derivative of gasdynamics is negative. In fact, as recently investigated, rarefaction shock waves are physically admissible in the inversion region. Within this project, several advancements with regards to the thermodynamic modeling of the fluids, the numerical simulation of the fluid flow and the cross-validation of the numerical results, and the robust optimization of some simple configuration, have been performed. Here we consider more classical finite-volume scheme (HLL scheme with a second-order spatial accuracy ensured by means of a MUSCL-type reconstruction).

4.3. High performance simulation dedicated to ITER project

Participants: Rémi Abgrall, Pierre Ramet.
In the context of a previous ANR project called ASTER (Adaptive MHD Simulation of Tokamak Elms for iteR), we have established a collaboration with the physicists of the CEA/DRFC group. The magneto-hydrodynamic instability called ELM for Edge Localized Mode is commonly observed in the standard tokamak operating scenario. The energy losses the ELM will induce in ITER plasmas are a real concern. However, the current understanding of what sets the size of these ELM induced energy losses is extremely limited. Recently, encouraging results on the simulation of an ELM cycle have been obtained with the JOREK code developed at CEA but at reduced toroidal resolution. The JOREK code uses a fully implicit time evolution scheme in conjunction with the PaStiX sparse matrix library.

To improve the order of the spatial representation of the variables and their gradients, the so-called Bezier finite elements have been developed and implemented in the JOREK code. This allows an accurate alignment of the finite elements with the magnetic geometry of tokamak plasmas. This alignment is necessary due to the large anisotropy of the physics behavior along and perpendicular to the magnetic fieldlines. The Bezier elements, an extension of the standard cubic Hermite elements, allow the local refinement of the elements. During a postdoctoral position, H. Sellama has implemented an adaptive refinement and successfully applied to a tearing instability test case and to the injection of pellets in the plasma.

The fully implicit time evolution scheme in the JOREK code leads to large sparse matrices which have to be solved at every time step. The MHD model leads to very badly conditioned matrices. In principle the PaStiX library can solve these large sparse using the direct method. However, for large 3D problems the CPU time for the direct solver becomes too large. Iterative solution methods require a preconditioner adapted to the problem. Many of the commonly used preconditioners have been tested but no satisfactory solution has been found. Instead, a physics based preconditioner has been constructed by using the diagonal block for each of the Fourier modes in the toroidale direction. This means the preconditioner represents the linear part of each harmonic but neglects the interaction between harmonics. This scheme leads independent matrices that are factorized and solved in parallel using the PaStiX solver. A GMRES iterative solver with the preconditioner has proved to be an efficient solver for the non-linear MHD code. The developments of the JOREK code in the ASTER project have allowed simulating ELMs with a much improved accuracy in a real 3D geometry. The typical problem size has increased from $5 \times 10^5$ unknowns to $9 \times 10^6$ unknowns. The largest cases have been run on 1500 processors.

We develop two kinds of software. The first one consists in generic libraries that are used within application codes. These libraries comprise a sequential and parallel partitioner for large irregular graphs or meshes (Scotch), a middleware library for distributed mesh handling (PaMPA), and high performance direct or hybrid solvers for very large sparse systems of equations (PaStiX and HIPS). The second kind of software corresponds to dedicated software for fluid mechanics including the team’s historical code RealfluID$^S$, and the more recent developments Aerosol, SLOWS, and COCA.

For parallel software developments, we use the message passing paradigm (basing on the MPI interface), sometimes combined with threads so as to exploit multi-core architectures at their best: in some computation kernels such as solvers, when processing elements reside on the same compute node, message buffer space can be saved because the aggregation of partial results can be performed directly in the memory of the receiving processing element. Memory savings can be tremendous, and help us achieve problem sizes which could not be reached before (see Section 5.5).
4. Application Domains

4.1. Application Domains

The application domains of Computer Aided Design are Aircraft Industry, Car Industry, Oil and Gas Industry, Architecture and Civil Engineering, NC Simulation, etc. The applications of Computer Graphics mainly are video games and film Industry.
4. Application Domains

4.1. Effusion cooling of aeronautical combustion chambers walls

The industrial applications of our project is the cooling of the walls of the combustion chambers encountered in the helicopter engines, and more precisely, we wish to contribute to the improvement of effusion cooling. Effusion cooling is nowadays very widespread, especially in the aeronautical context. It consists in piercing holes on the wall of the combustion chamber. These holes induce cold jets that enter inside the combustion chamber. The goal of this jet is to form a film of air that will cool the walls of the chamber, see Figure 2.

Figure 2. Effusion cooling of aeronautical combustion chambers: close view of a typical perforated chamber wall

Effusion cooling in a combustion chamber takes at the wall where thousands of small holes allow cool air to enter inside the combustion chamber. This induces jets in crossflow in charge of cooling the walls, whatever the heat and the acoustic waves present inside the chamber. Nevertheless, this technique is not straightforward to put in practice: the size, design and position of the holes can have an important effect on the cooling efficiency. For a safe and efficient functioning of the combustion chamber, it is required that the cooling jets and the combustion effects be as much independent as possible. For example, this means that

- The jets of cool air should not mix too much with the internal flow. Otherwise it will decrease the efficiency of the combustion.
- The jets should be as much stable as possible when submitted to waves emitted in the combustion chamber, e.g. acoustic waves induced by combustion instabilities. Otherwise the jets may not cool enough the walls of the combustion chamber which can then undergoes severe damages.
The first point is what we aim at simulate in this project. As the model chosen is the fully compressible Navier Stokes system, there should not be any problem in the future for being able to simulate the effect of an acoustic forcing on the jet in crossflow.

Having a database of Direct Numerical Simulations is also fundamental for testing closure laws that are used in turbulence models encountered in RANS and LES models. With such models, it is possible for example to perform optimisation.

A last aspect, that will not be dealt with in this project, but that could be dealt with in the future, is the interaction between the flow and the wall. The aim is to understand the effect of coupling between the heat propagation in the wall and the flow near the wall. A careful study of this interaction can allow to determine the exchange coefficients, and so the efficiency of the cooling by the jet. Such determination may particularly useful to develop one or multidimensional models of wall-fluid interaction [23].

From the application point of view, compressibility effects must be taken into account since the Mach number of the flow can reach values equal to 0.3, hence/or acoustic waves may be present inside the combustion chamber. This can raise a problem, because upwind numerical schemes are known to be less accurate in the low Mach limit.
4. Application Domains

4.1. Thermonuclear fusion

Controlled fusion is one of the major prospects for a long term source of energy. Two main research directions are studied: magnetic fusion where the plasma is confined in tokamaks using a large external magnetic field and inertial fusion where the plasma is confined thanks to intense laser or particle beams. The simulation tools we develop can be applied for both approaches.

Controlled fusion is one of the major challenges of the 21st century that can answer the need for a long term source of energy that does not accumulate wastes and is safe. The nuclear fusion reaction is based on the fusion of atoms like Deuterium and Tritium. These can be obtained from the water of the oceans that is widely available and the reaction does not produce long-term radioactive wastes, unlike today’s nuclear power plants which are based on nuclear fission.

Two major research approaches are followed towards the objective of fusion based nuclear plants: magnetic fusion and inertial fusion. In order to achieve a sustained fusion reaction, it is necessary to confine sufficiently the plasma for a long enough time. If the confinement density is higher, the confinement time can be shorter but the product needs to be greater than some threshold value.

The idea behind magnetic fusion is to use large toroidal devices called tokamaks in which the plasma can be confined thanks to large applied magnetic field. The international project ITER\(^1\) is based on this idea and aims to build a new tokamak which could demonstrate the feasibility of the concept.

The inertial fusion concept consists in using intense laser beams or particle beams to confine a small target containing the Deuterium and Tritium atoms. The Laser Mégajoule which is being built at CEA in Bordeaux will be used for experiments using this approach.

Nonlinear wave-wave interactions are primary mechanisms by which nonlinear fields evolve in time. Understanding the detailed interactions between nonlinear waves is an area of fundamental physics research in classical field theory, hydrodynamics and statistical physics. A large amplitude coherent wave will tend to couple to the natural modes of the medium it is in and transfer energy to the internal degrees of freedom of that system. This is particularly so in the case of high power lasers which are monochromatic, coherent sources of high intensity radiation. Just as in the other states of matter, a high laser beam in a plasma can give rise to stimulated Raman and Brillouin scattering (respectively SRS and SBS). These are three wave parametric instabilities where two small amplitude daughter waves grow exponentially at the expense of the pump wave, once phase matching conditions between the waves are satisfied and threshold power levels are exceeded. The illumination of the target must be uniform enough to allow symmetric implosion. In addition, parametric instabilities in the underdense coronal plasma must not reflect away or scatter a significant fraction of the incident light (via SRS or SBS), nor should they produce significant levels of hot electrons (via SRS), which can preheat the fuel and make its isentropic compression far less efficient. Understanding how these deleterious parametric processes function, what non uniformities and imperfections can degrade their strength, how they saturate and interdepend, all can benefit the design of new laser and target configuration which would minimize their undesirable features in inertial confinement fusion. Clearly, the physics of parametric instabilities must be well understood in order to rationally avoid their perils in the varied plasma and illumination conditions which will be employed in the National Ignition Facility or LMJ lasers. Despite the thirty-year history of the field, much remains to be investigated.

\(^1\) [http://www.iter.org](http://www.iter.org)
Our work in modelling and numerical simulation of plasmas and particle beams can be applied to problems like laser-matter interaction, the study of parametric instabilities (Raman, Brillouin), the fast ignitor concept in the laser fusion research as well as for the transport of particle beams in accelerators. Another application is devoted to the development of Vlasov gyrokinetic codes in the framework of the magnetic fusion programme in collaboration with the Department of Research on Controlled Fusion at CEA Cadarache. Finally, we work in collaboration with the American Heavy Ion Fusion Virtual National Laboratory, regrouping teams from laboratories in Berkeley, Livermore and Princeton on the development of simulation tools for the evolution of particle beams in accelerators.

4.2. Nanophysics

Kinetic models like the Vlasov equation can also be applied for the study of large nano-particles as approximate models when ab initio approaches are too costly.

In order to model and interpret experimental results obtained with large nano-particles, ab initio methods cannot be employed as they involve prohibitive computational times. A possible alternative resorts to the use of kinetic methods originally developed both in nuclear and plasma physics, for which the valence electrons are assimilated to an inhomogeneous electron plasma. The LPMIA (Nancy) possesses a long experience on the theoretical and computational methods currently used for the solution of kinetic equation of the Vlasov and Wigner type, particularly in the field of plasma physics.

Using a Vlasov Eulerian code, we have investigated in detail the microscopic electron dynamics in the relevant phase space. Thanks to a numerical scheme recently developed by Filbet et al. [66], the fermionic character of the electron distribution can be preserved at all times. This is a crucial feature that allowed us to obtain numerical results over long times, so that the electron thermalization in confined nano-structures could be studied.

The nano-particle was excited by imparting a small velocity shift to the electron distribution. In the small perturbation regime, we recover the results of linear theory, namely oscillations at the Mie frequency and Landau damping. For larger perturbations nonlinear effects were observed to modify the shape of the electron distribution.

For longer time, electron thermalization is observed: as the oscillations are damped, the center of mass energy is entirely converted into thermal energy (kinetic energy around the Fermi surface). Note that this thermalization process takes place even in the absence of electron-electron collisions, as only the electric mean-field is present.
4. Application Domains

4.1. Aerodynamics

Aerodynamics provide a challenging field for numerical simulations in fluid dynamics with a wide range of applications. Robustness of the simulation software with respect to physical parameters as the Reynolds and Mach numbers is necessary condition. In general, realistic simulations need to be done in three dimensions, which makes the efficiency of the numerical approach and implementation a question of feasibility. Therefore, different efforts are made in this project in order to tackle these subjects.

4.2. Viscoelastic flows

Polymeric fluids are, from a rheological point of view, viscoelastic non-Newtonian fluids, see Figure 3. Their specific behavior can be observed in a variety of physical phenomena, which are unseen with Newtonian liquids and which cannot be predicted by the Navier-Stokes equations. The better known examples include the rod climbing Weissenberg effect, die swell and extrusion instabilities (cf. fig. 1). The rheological behavior of polymers is so complex that many different constitutive equations have been proposed in the literature in order to describe these phenomena, see for instance [72]. The choice of an appropriate constitutive law is still a central problem. We consider realistic constitutive equations such as the Giesekus model. In comparison to the classical models used in CFD, such as UCM or Oldroyd B fluids, the Giesekus model is characterized by a quadratic stress term. It is important to understand the theoretical properties of the Giesekus model. As outlined above, energy estimates are crucial for the development of robust numerical schemes, see also the recent work on similar questions in the EPI MICMAC [51], [64].

Our aim is to develop new algorithms for the discretization of polymer models, which should be efficient and robust for $We > 10$. For this purpose, we will develop a mathematical approach based on recent ideas on discretizations preserving the positivity of the conformation tensor. This property is believed to be crucial in order to avoid numerical instabilities associated with large Weissenberg numbers. In order to develop monotone numerical schemes, we use recent discretization techniques such as stabilized finite element and discontinuous Galerkin methods. We have validated our code at hand of academic benchmark problems in comparison with the commercial code PolyFlow®.
The result of a computation of a 4:1-contraction, comparing Newtonian flow with Giesekus model, is shown in Figure 4. In the same figure, a comparison of the computed profile in the channel with the one obtained by the PolyFlow® , both on a relatively coarse mesh, is shown. A precise study shows that the results are in good agreement for moderate Weissenberg numbers $W_e$; the computation time is by a factor of two smaller for the preliminary version of our code based on triangular meshes. For $W_e > 20$, we were not able to get a converged solution with the commercial code, whereas our program yields stationary solutions up to $W_e \approx 30$.

Further improvements are expected from the use of adaptivity, as well as from the implementation of adequate iterative solvers. The long-term goal is to successively build up robust and efficient software tools in order to tackle design problems, such as the design of mixing devices.

4.3. Heat transfer

Heat transfer problems involve the coupling of the flow field of the fluid with temperature inside the flow and possibly on the boundary of the flow domain. A typical example of a heat transfer problem is the cooling of a combustion engine, see the project Optimal described in Section 7.1.

4.4. Turbulence

Turbulent flows are ubiquitous in industrial applications. Direct numerical simulation (DNS), which aims at complete resolution of the flow field up to the Kolmogorov scale, has historically been limited to very simple geometries. The increase of computational power and the development of specialized numerical methods open the door to a wider range of applications. However, for most applications of practical interest, the use of some kind of turbulence modeling is unavoidable in order to obtain the prediction of averaged values and commercial software is in general based on such approaches combined with wall laws. In many applications, such as the project Optimal, see Section 7.1, the Reynolds number is at an intermediate level, which means that the turbulence is not fully developed, and the heuristics behind most turbulence models are questionable. Especially, in heat transfer problems, the usage of wall laws seems to considerably lower the accuracy of the predicted mean values. In order to improve the computation of such values, we are particularly interested in variational multiscale methods and its relations to stabilized finite element methods.

4.5. Flows in porous media

Flows in fractured porous media are very important in petroleum engineering. They represent a good framework for the application of the tools developed in the CONCHA library such as the NXFEM method, goal oriented adaptivity, multiscale coupling of different models and multilevel solvers.
4. Application Domains

4.1. Radar and GPR applications

Conventional radar imaging techniques (ISAR, GPR, ...) use backscattering data to image targets. The commonly used inversion algorithms are mainly based on the use of weak scattering approximations such as the Born or Kirchhoff approximation leading to very simple linear models, but at the expense of ignoring multiple scattering and polarization effects. The success of such an approach is evident in the wide use of synthetic aperture radar techniques.

However, the use of backscattering data makes 3-D imaging a very challenging problem (it is not even well understood theoretically) and as pointed out by Brett Borden in the context of airborne radar: “In recent years it has become quite apparent that the problems associated with radar target identification efforts will not vanish with the development of more sensitive radar receivers or increased signal-to-noise levels. In addition it has (slowly) been realized that greater amounts of data - or even additional “kinds” of radar data, such as added polarization or greatly extended bandwidth - will all suffer from the same basic limitations affiliated with incorrect model assumptions. Moreover, in the face of these problems it is important to ask how (and if) the complications associated with radar based automatic target recognition can be surmounted.” This comment also applies to the more complex GPR problem.

Our research themes will incorporate the development, analysis and testing of several novel methods, such as sampling methods, level set methods or topological gradient methods, for ground penetrating radar application (imaging of urban infrastructures, landmines detection, underground waste deposits monitoring, ...) using multistatic data.

4.2. Biomedical imaging

Among emerging medical imaging techniques we are particularly interested in those using low to moderate frequency regimes. These include Microwave Tomography, Electrical Impedance Tomography and also the closely related Optical Tomography technique. They all have the advantage of being potentially safe and relatively cheap modalities and can also be used in complementarity with well established techniques such as X-ray computed tomography or Magnetic Resonance Imaging.

With these modalities tissues are differentiated and, consequentially can be imaged, based on differences in dielectric properties (some recent studies have proved that dielectric properties of biological tissues can be a strong indicator of the tissues functional and pathological conditions, for instance, tissue blood content, ischemia, infarction, hypoxia, malignancies, edema and others). The main challenge for these functionalities is to built a 3-D imaging algorithm capable of treating multi-static measurements to provide real-time images with highest (reasonably) expected resolutions and in a sufficiently robust way.

Another important biomedical application is brain imaging. We are for instance interested in the use of EEG and MEG techniques as complementary tools to MRI. They are applied for instance to localize epileptic centers or active zones (functional imaging). Here the problem is different and consists into performing passive imaging: the epileptic centers act as electrical sources and imaging is performed from measurements of induced currents. Incorporating the structure of the skull is primordial in improving the resolution of the imaging procedure. Doing this in a reasonably quick manner is still an active research area, and the use of asymptotic models would offer a promising solution to fix this issue.
4.3. Non destructive testing and parameter identification

One challenging problem in this vast area is the identification and imaging of defaults in anisotropic media. For instance this problem is of great importance in aeronautical constructions due to the growing use of composite materials. It also arises in applications linked with the evaluation of wood quality, like locating knots in timber in order to optimize timber-cutting in sawmills, or evaluating wood integrity before cutting trees. The anisotropy of the propagative media renders the analysis of diffracted waves more complex since one cannot only relies on the use of backscattered waves. Another difficulty comes from the fact that the micro-structure of the media is generally not well known a priori.

Our concern will be focused on the determination of qualitative information on the size of defaults and their physical properties rather than a complete imaging which for anisotropic media is in general impossible. For instance, in the case of homogeneous background, one can link the size of the inclusion and the index of refraction to the first eigenvalue of so-called interior transmission problem. These eigenvalues can be determined form the measured data and a rough localization of the default. Our goal is to extend this kind of idea to the cases where both the propagative media and the inclusion are anisotropic. The generalization to the case of cracks or screens has also to be investigated.

In the context of nuclear waste management many studies are conducted on the possibility of storing waste in a deep geological clay layer. To assess the reliability of such a storage without leakage it is necessary to have a precise knowledge of the porous media parameters (porosity, tortuosity, permeability, etc.). The large range of space and time scales involved in this process requires a high degree of precision as well as tight bounds on the uncertainties. Many physical experiments are conducted in situ which are designed for providing data for parameters identification. For example, the determination of the damaged zone (caused by excavation) around the repository area is of paramount importance since microcracks yield drastic changes in the permeability. Level set methods are a tool of choice for characterizing this damaged zone.

4.4. Diffusion MRI

- Detecting physiological and pathological conditions that are accompanied by higher or lower than normal diffusion MRI signal attenuation. Examples: immediately after stroke, there is a large drop in the measured apparent diffusion coefficient; demyelinating diseases of the central nervous system have been indicated by higher than normal radial diffusivity.
- Evaluating cancer treatment by quantifying tumor cellularity based on diffusion MRI measurements. Tumor cellularity is shown to be inversely correlated to measured diffusivity.
GAMMA3 Project-Team (section vide)
4. Application Domains

4.1. Laser physics

Laser physics considers the propagation over long space (or time) scales of high frequency waves. Typically, one has to deal with the propagation of a wave having a wavelength of the order of $10^{-6} \text{m}$, over distances of the order $10^{-2} \text{m}$ to $10^{4} \text{m}$. In these situations, the propagation produces both a short-scale oscillation and exhibits a long term trend (drift, dispersion, nonlinear interaction with the medium, or so), which contains the physically important feature. For this reason, one needs to develop ways of filtering the irrelevant high-oscillations, and to build up models and/or numerical schemes that do give information on the long-term behavior. In other terms, one needs to develop high-frequency models and/or high-frequency schemes.

This task has been partially performed in the context of a contract with Alcatel, in that we developed a new numerical scheme to discretize directly the high-frequency model derived from physical laws.

Generally speaking, the demand in developing such models or schemes in the context of laser physics, or laser/matter interaction, is large. It involves both modeling and numerics (description of oscillations, structure preserving algorithms to capture the long-time behaviour, etc).

In a very similar spirit, but at a different level of modelling, one would like to understand the very coupling between a laser propagating in, say, a fiber, and the atoms that build up the fiber itself.

The standard, quantum, model in this direction is called the Bloch model: it is a Schrödinger like equation that describes the evolution of the atoms, when coupled to the laser field. Here the laser field induces a potential that acts directly on the atom, and the link between this potential and the laser itself is given by the so-called dipolar matrix, a matrix made up of physical coefficients that describe the polarization of the atom under the applied field.

The scientific objective here is twofold. First, one wishes to obtain tractable asymptotic models that average out the high oscillations of the atomic system and of the laser field. A typical phenomenon here is the resonance between the field and the energy levels of the atomic system. Second, one wishes to obtain good numerical schemes in order to solve the Bloch equation, beyond the oscillatory phenomena entailed by this model.

4.2. Molecular Dynamics

In classical molecular dynamics, the equations describe the evolution of atoms or molecules under the action of forces deriving from several interaction potentials. These potentials may be short-range or long-range and are treated differently in most molecular simulation codes. In fact, long-range potentials are computed at only a fraction of the number of steps. By doing so, one replaces the vector field by an approximate one and alternates steps with the exact field and steps with the approximate one. Although such methods have been known and used with success for years, very little is known on how the “space” approximation (of the vector field) and the time discretization should be combined in order to optimize the convergence. Also, the fraction of steps where the exact field is used for the computation is mainly determined by heuristic reasons and a more precise analysis seems necessary. Finally, let us mention that similar questions arise when dealing with constrained differential equations, which are a by-product of many simplified models in molecular dynamics (this is the case for instance if one replaces the highly-oscillatory components by constraints).
4. Application Domains

4.1. Introduction
We now present our contribution to these above challenges concerning interface problem for complex fluids, direct simulations and analysis, flow control and optimization. From the technical point of view, many productions are common to the different parts of the project. For example, level-set methods, fast-marching procedure are used for shape optimization and for microfluidics, penalization methods are used for high Reynolds flows and for tumor growth. This leads to a strong politic of development of numerical modules.

4.2. Multi-fluid flows
- computation of bifluid flows: see the thesis of S. Tancogne ([77]) and P. Vigneaux ([80]). Stability of an interface, shape of droplets, formation of a jet. Study of the Plateau-Rayleigh instability. Behaviour of diphasic fluids evolving in square microchannels.
- emulsions and foam: see the thesis of S. Benito [45]. Applications in biology: behaviour of tissues, of tumor....
- polymer nanotube conglomerate wire: it was the subject of a talk in the following conference "WCCM8-ECCOMAS2008" and of the talk [59].

4.3. Cancer modeling
- specific models: investigation of two particular cancer: gliomas (brain tumors), colorectal cancers lung and lever metastasis, brest cancer. This is one part of the PhD works of J.B. Lagaert and D. Lombardi.
- modelling of electrochemotherapy: see ARC C3MB (http://www.math.u-bordeaux1.fr/ArcC3MB/)
- parameter estimations with the help of low order models: see the PhD of J.B. Lagaert and D. Lombardi
- patient-specific simulations
- optimal shape design: the goal is to recover the vascularization of a model tumor from the knowledge of its shape evolution. See F. Chantalat [56].

4.4. Newtonian fluid flows simulations and their analysis
- simulation of a synthetic or pulsed jet. This is an ongoing project with Renault and PSA inside a PREDIT project.
- vortex dynamics: see [63].
- simulation of compressible flows on cartesian grids: see the thesis of Gabriele Ottino’s Thesis [73], who underwent his doctoral studies in conjunction in the MC2 team and at the Politecnico di Torino, and defended in April 2009. He had a grant of the French-Italian university.
- 3D turbulent flows through DESGRIVRE contract with AIRBUS. Thesis of C. Wervaecke [82]. The goal is to use Detached-Eddy Simulation to model turbulent flows around iced bodies.
porous media: Numerical study of coupling between Richards and transport-diffusion equations in permeable sediment affected by tidal oscillation. See the thesis of R. Chassagne [57]

4.5. Flow control and shape optimization

- passive control: the idea is to put a porous interface between the solid body and the fluid. See the D. Depeyras thesis [62], Yong-Liang Xiang [84] and CH Bruneau and Iraj Mortazavi [48]. See also project [53] founded by the European Community.
- active control: see the three PhD thesis: M. Buffoni, J. Weller [81], E. Lombardi and FFAST project funded by EU and led by the University of Bristol and AIRBUS UK.
- shape optimization for turbo-machines: See [78].
- reduced order models: it consists in designing a non-linear observer that estimates the state of the flow field from a limited number of measurements in the field. The challenge is to reduce as much as possible the information required and to take it from the boundary. See J. Weller [81] and E. Lombardi.
- passive control of flows with porous media: see [50], [47], [46], [72], [51].
- inverse problems in imagery: see [55].
4. Application Domains

4.1. Electronic structure of large systems

As the size of the systems one wants to study increases, more efficient numerical techniques need to be resorted to. In computational chemistry, the typical scaling law for the complexity of computations with respect to the size of the system under study is \(N^3\), \(N\) being for instance the number of electrons. The Holy Grail in this respect is to reach a linear scaling, so as to make possible simulations of systems of practical interest in biology or material science. Efforts in this direction must address a large variety of questions such as

- how can one improve the nonlinear iterations that are the basis of any \textit{ab initio} models for computational chemistry?
- how can one more efficiently solve the inner loop which most often consists in the solution procedure for the linear problem (with frozen nonlinearity)?
- how can one design a sufficiently small variational space, whose dimension is kept limited while the size of the system increases?

An alternative strategy to reduce the complexity of \textit{ab initio} computations is to try to couple different models at different scales. Such a mixed strategy can be either a sequential one or a parallel one, in the sense that

- in the former, the results of the model at the lower scale are simply used to evaluate some parameters that are inserted in the model for the larger scale: one example is the parameterized classical molecular dynamics, which makes use of force fields that are fitted to calculations at the quantum level;
- while in the latter, the model at the lower scale is concurrently coupled to the model at the larger scale: an instance of such a strategy is the so called QM/MM coupling (standing for Quantum Mechanics/Molecular Mechanics coupling) where some part of the system (typically the reactive site of a protein) is modeled with quantum models, that therefore accounts for the change in the electronic structure and for the modification of chemical bonds, while the rest of the system (typically the inert part of a protein) is coarse grained and more crudely modeled by classical mechanics.

The coupling of different scales can even go up to the macroscopic scale, with methods that couple a microscopic description of matter, or at least a mesoscopic one, with the equations of continuum mechanics at the macroscopic level.

4.2. Computational Statistical Mechanics

The orders of magnitude used in the microscopic description of matter are far from the orders of magnitude of the macroscopic quantities we are used to: The number of particles under consideration in a macroscopic sample of material is of the order of the Avogadro number \(N_A \sim 10^{23}\), the typical distances are expressed in Å (10\(^{-10}\) m), the energies are of the order of \(kT \approx 4 \times 10^{-21}\) J at room temperature, and the typical times are of the order of 10\(^{-15}\) s when the proton mass is the reference mass.

To give some insight into such a large number of particles contained in a macroscopic sample, it is helpful to compute the number of moles of water on earth. Recall that one mole of water corresponds to 18 mL, so that a standard glass of water contains roughly 10 moles, and a typical bathtub contains 10\(^5\) mol. On the other hand, there are approximately 1.3 \(\times\) 10\(^{18}\) m\(^3\) of water in the oceans, \textit{i.e.} 7.2 \(\times\) 10\(^{22}\) mol, a number comparable to the Avogadro number. This means that inferring the macroscopic behavior of physical systems described at the microscopic level by the dynamics of several millions of particles only is like inferring the ocean’s dynamics from hydrodynamics in a bathtub...
For practical numerical computations of matter at the microscopic level, following the dynamics of every atom would require simulating \( N_A \) atoms and performing \( O(10^{15}) \) time integration steps, which is of course impossible! These numbers should be compared with the current orders of magnitude of the problems that can be tackled with classical molecular simulation, where several millions of atoms only can be followed over time scales of the order of 0.1 \( \mu s \).

Describing the macroscopic behavior of matter knowing its microscopic description therefore seems out of reach. Statistical physics allows us to bridge the gap between microscopic and macroscopic descriptions of matter, at least on a conceptual level. The question is whether the estimated quantities for a system of \( N \) particles correctly approximate the macroscopic property, formally obtained in the thermodynamic limit \( N \to +\infty \) (the density being kept fixed). In some cases, in particular for simple homogeneous systems, the macroscopic behavior is well approximated from small-scale simulations. However, the convergence of the estimated quantities as a function of the number of particles involved in the simulation should be checked in all cases.

Despite its intrinsic limitations on spatial and timescales, molecular simulation has been used and developed over the past 50 years, and its number of users keeps increasing. As we understand it, it has two major aims nowadays.

First, it can be used as a **numerical microscope**, which allows us to perform “computer” experiments. This was the initial motivation for simulations at the microscopic level: physical theories were tested on computers. This use of molecular simulation is particularly clear in its historic development, which was triggered and sustained by the physics of simple liquids. Indeed, there was no good analytical theory for these systems, and the observation of computer trajectories was very helpful to guide the physicists’ intuition about what was happening in the system, for instance the mechanisms leading to molecular diffusion. In particular, the pioneering works on Monte-Carlo methods by Metropolis et al, and the first molecular dynamics simulation of Alder and Wainwright were performed because of such motivations. Today, understanding the behavior of matter at the microscopic level can still be difficult from an experimental viewpoint (because of the high resolution required, both in time and in space), or because we simply do not know what to look for! Numerical simulations are then a valuable tool to test some ideas or obtain some data to process and analyze in order to help assessing experimental setups. This is particularly true for current nanoscale systems.

Another major aim of molecular simulation, maybe even more important than the previous one, is to compute macroscopic quantities or thermodynamic properties, typically through averages of some functionals of the system. In this case, molecular simulation is a way to obtain **quantitative** information on a system, instead of resorting to approximate theories, constructed for simplified models, and giving only qualitative answers. Sometimes, these properties are accessible through experiments, but in some cases only numerical computations are possible since experiments may be unfeasible or too costly (for instance, when high pressure or large temperature regimes are considered, or when studying materials not yet synthesized). More generally, molecular simulation is a tool to explore the links between the microscopic and macroscopic properties of a material, allowing one to address modelling questions such as “Which microscopic ingredients are necessary (and which are not) to observe a given macroscopic behavior?”

### 4.3. Homogenization and related problems

Over the years, the project-team has developed an increasing expertise on how to couple models written at the atomistic scale, with more macroscopic models, and, more generally, an expertise in multiscale modelling for materials science.

The following observation motivates the idea of coupling atomistic and continuum description of materials. In many situations of interest (crack propagation, presence of defects in the atomistic lattice, ...), using a model based on continuum mechanics is difficult. Indeed, such a model is based on a macroscopic constitutive law, the derivation of which requires a deep qualitative and quantitative understanding of the physical and mechanical properties of the solid under consideration. For many solids, reaching such an understanding is a challenge, as loads they are submitted to become larger and more diverse, and as experimental observations
helping designing such models are not always possible (think of materials used in the nuclear industry). Using
an atomistic model in the whole domain is not possible either, due to its prohibitive computational cost. Recall
indeed that a macroscopic sample of matter contains a number of atoms on the order of $10^{23}$. However, it turns
out that, in many situations of interest, the deformation that we are after is not smooth in only a small part of
the solid. So, a natural idea is to try to take advantage of both models, the continuum mechanics one and the
atomistic one, and to couple them, in a domain decomposition spirit. In most of the domain, the deformation is
expected to be smooth, and reliable continuum mechanics models are then available. In the rest of the domain,
the expected deformation is singular, one needs an atomistic model to describe it properly, the cost of which
remains however limited as this region is small.

From a mathematical viewpoint, the question is to couple a discrete model with a model described by PDEs. This raises many questions, both from the theoretical and numerical viewpoints:

- first, one needs to derive, from an atomistic model, continuum mechanics models, under some reg-
  ularity assumptions that encode the fact that the situation is smooth enough for such a macroscopic
  model to be a good description of the materials;

- second, couple these two models, e.g. in a domain decomposition spirit, with the specificity that
  models in both domains are written in a different language, that there is no natural way to write
  boundary conditions coupling these two models, and that one would like the decomposition to be
  self-adaptive.

More generally, the presence of numerous length-scales in material science problems represents a challenge
for numerical simulation, especially when some randomness is assumed on the materials. It can take various
forms, and includes defects in crystals, thermal fluctuations, and impurities or heterogeneities in continuous
media. Standard methods available in the literature to handle such problems often lead to very costly
computations. Our goal is to develop numerical methods that are more affordable. Because we cannot embrace
all difficulties at once, we focus on a simple case, where the fine scale and the coarse-scale models can be
written similarly, in the form of a simple elliptic partial differential equation in divergence form. The fine scale
model includes heterogeneities at a small scale, a situation which is formalized by the fact that the coefficients
in the fine scale model vary on a small length scale. After homogenization, this model yields an effective,
macroscopic model, which includes no small scale. In many cases, a sound theoretical groundwork exists for
such homogenization results. We consider mostly the setting of stochastic homogenization of linear, scalar,
second order elliptic PDEs, where analytical formulas for the effective properties are known. The difficulty
stems from the fact that they generally lead to prohibitively costly computations. For such a case, simple
from the theoretical viewpoint, our aim is to focus on different practical computational approaches to speed-up
the computations. One possibility, among others, is to look for specific random materials, relevant from
the practical viewpoint, and for which a dedicated approach can be proposed, that is less expensive than the
general approach.
4. Application Domains

4.1. Computational electromagnetics

Electromagnetism has found and continues to find applications in a wide array of areas, encompassing both industrial and societal purposes. Applications of current interest include those related to communications (e.g. transmission through optical fiber lines), to biomedical devices and health (e.g. tomography, power-line safety, etc.), to circuit or magnetic storage design (electromagnetic compatibility, hard disc operation), to geophysical prospecting, and to non-destructive evaluation (e.g. crack detection), to name but just a few. Although the principles of electromagnetics are well understood, their application to practical configurations of current interest is significantly complicated and far beyond manual calculation in all but the simplest cases. These complications typically arise from the geometrical characteristics of the propagation medium (irregular shapes, geometrical singularities), the physical characteristics of the propagation medium (heterogeneity, physical dispersion and dissipation) and the characteristics of the sources (wires, etc.). The significant advances in computer technology that have taken place over the last two decades have been such that numerical modeling and computer simulation is nowadays ubiquitous in the study of electromagnetic interactions. The team is actively contributing to the design of advanced numerical methodologies for the solution of the PDE models of electromagnetism with a focus on problems relevant to computational bioelectromagnetics i.e. which require the simulation of the interaction of electromagnetic waves with biological tissues. Applications are concerned with the evaluation of potential sanitary effects of human exposure to electromagnetic waves (see Fig. 1 ), or with the design of biomedical devices and systems (i.e. imaging systems, implantable antennas, etc.).

4.2. Computational geoseismics

Computational challenges in geoseismics span a wide range of disciplines and have significant scientific and societal implications. Two important topics are mitigation of seismic hazards and discovery of economically recoverable petroleum resources. The team is before all considering the fist of these topics. Indeed, to understand the basic science of earthquakes and to help engineers better prepare for such an event, scientists want to identify which regions are likely to experience the most intense shaking, particularly in populated sediment-filled basins. This understanding can be used to improve building codes in high risk areas and to help engineers design safer structures, potentially saving lives and property. In the absence of deterministic earthquake prediction, forecasting of earthquake ground motion based on simulation of scenarios is one of the most promising tools to mitigate earthquake related hazards. This requires intense modeling that meets the spatial and temporal resolution scales of the continuously increasing density and resolution of the seismic instrumentation, which record dynamic shaking at the surface, as well as of the basin models. Another important issue is to improve our physical understanding of the earthquake rupture processes and seismicity. Large-scale simulations of earthquake rupture dynamics, and of fault interactions, are currently the only means to investigate these multi-scale physics together with data assimilation and inversion. High resolution models are also required to develop and assess fast operational analysis tools for real time seismology and early warning systems. Modeling and forecasting earthquake ground motion in large basins is a challenging and complex task. The complexity arises from several sources. First, multiple scales characterize the earthquake source and basin response: the shortest wavelengths are measured in tens of meters, whereas the longest measure in kilometers; basin dimensions are on the order of tens of kilometers, and earthquake sources up to hundreds of kilometers. Second, temporal scales vary from the hundredth of a second necessary to resolve the highest frequencies of the earthquake source up to as much as several minutes of shaking within the basin. Third, many basins have a highly irregular geometry. Fourth, the soil’s material properties are highly heterogeneous. And fifth, geology and source parameters are observable only indirectly and thus introduce uncertainty in the modeling process. In this context, the team undertakes research and development activites
Figure 1. Exposure of head tissues to an electromagnetic wave emitted by a localized source. Top figures: surface triangulations of the skin and the skull. Bottom figures: contour lines of the amplitude of the electric field.
aiming at the design of numerical modeling strategies for accurately and efficiently handling the interaction of seismic waves generated by an earthquake source with complex geological media. These activities are conducted in the framework of a collaboration with CETE Méditerranée http://www.cete-mediterranee.fr/gb which is a regional technical and engineering centre whose activities are concerned with seismic risk assessment studies.
NANO-D Team

4. Application Domains

4.1. Overview

NANO-D is a priori concerned with all applications domains involving atomistic representations, including chemistry, physics, electronics, material science, biology, etc.

Historically, though, our first applications have been in biology, as the next two sections detail. Thanks to the development of algorithms to efficiently simulate reactive force fields, as well as to perform interactive quantum mechanical calculations, however, we now have the possibility to address problems in chemistry, and physics.

4.2. Structural Biology

Structural biology is a branch of molecular biology, biochemistry, and biophysics concerned with the molecular structure of biological macromolecules, especially proteins and nucleic acids. Structural biology studies how these macromolecules acquire the structures they have, and how alterations in their structures affect their function. The methods that structural biologists use to determine the structure typically involve measurements on vast numbers of identical molecules at the same time, such as X-Ray crystallography, NMR, cryo-electron microscopy, etc. In many cases these methods do not directly provide the structural answer, therefore new combinations of methods and modeling techniques are often required to advance further.

We develop a set of tools that help biologists to model structural features and motifs not resolved experimentally and to understand the function of different structural fragments.

- Symmetry is a frequent structural trait in molecular systems. For example, most of the water-soluble and membrane proteins found in living cells are composed of symmetrical subunits, and nearly all structural proteins form long oligomeric chains of identical subunits. Only a limited number of symmetry groups is allowed in crystallography, and thus, in many cases the native macromolecular conformation is not present on high-resolution X-ray structures. Therefore, to understand the realistic macromolecular packing, modeling techniques are required.

- Many biological experiments are rather costly and time-demanding. For instance, the complexity of mutagenesis experiments grows exponentially with the number of mutations tried simultaneously. In other experiments, many candidates are tried to obtain a desired function. For example, about 250,000 candidates were tested for the recently discovered antibiotic Platensimycin. Therefore, there is a vast need in advance modeling techniques that can predict interactions and foresee the function of new structures.

- Structure of many macromolecules is still unknown. For other complexes, it is known only partially. Thus, software tools and new algorithms are needed by biologists to model missing structural fragments or predict the structure of those molecule, where there is no experimental structural information available.

4.3. Pharmaceutics and Drug Design

Drug design is the inventive process of finding new medications based on the knowledge of the biological target. The drug is most commonly an organic small molecule which activates or inhibits the function of a biomolecule such as a protein, which in turn results in a therapeutic benefit to the patient. In the most basic sense, drug design involves design of small molecules that are complementary in shape and charge to the biomolecular target to which they interact and therefore will bind to it. Drug design frequently relies on computer modeling techniques. This type of modeling is often referred to as computer-aided drug design.
Structure-based drug design attempts to use the structure of proteins as a basis for designing new ligands by applying accepted principles of molecular recognition. The basic assumption underlying structure-based drug design is that a good ligand molecule should bind tightly to its target. Thus, one of the most important principles for designing or obtaining potential new ligands is to predict the binding affinity of a certain ligand to its target and use it as a criterion for selection.

We develop new methods to estimate the binding affinity using an approximation to the binding free energy. This approximation is assumed to depend on various structural characteristics of a representative set of native complexes with their structure solved to a high resolution. We study and verify different structural characteristics, such as radial distribution functions, and their effect on the binding free energy approximation.

### 4.4. Nano-engineering

![Figure 4. Snapshots of a nanotube capping process with the adaptive interactive modeler. Thanks to the adaptive methodology, this operation can be done in a few minutes.](image)

The magazine Science has recently featured a paper demonstrating an example of DNA nanotechnology, where DNA strands are stacked together through programmable self-assembly. In February 2007, the cover of Nature Nanotechnology showed a “nano-wheel” composed of a few atoms only. Several nanosystems have already been demonstrated, including a wheelbarrow molecule, a nano-car and a Morse molecule, etc. Typically, these nanosystems are designed in part via quantum mechanics calculations, such as the semi-empirical ASED+ calculation technique.
Figure 5. Different steps to prototype a “nano-pillow” with the adaptive interactive modeler.
Of course, not all small systems that currently fall under the label “nano” have mechanical, electronic, optical properties similar to the examples given above. Furthermore, current construction capabilities lack behind some of the theoretical designs which have been proposed. However, the trend is clearly for adding more and more functionality to nanosystems. While designing nanosystems is still very much an art mostly performed by physicists, chemists and biologists in labs throughout the world, there is absolutely no doubt that fundamental engineering practices will progressively emerge, and that these practices will be turned into quantitative rules and methods. Similar to what has happened with macroscopic engineering, powerful and generic software will then be employed to engineer complex nanosystems.

We have recently shown that our incremental and adaptive algorithms allow us to easily edit and model complex shapes, such as a nanotube (Fig. 4) and the “nano-pillow” below (Fig. 5).
4. Application Domains

4.1. Aeronautics and space

The demand of the aeronautical industry remains very strong in aerodynamics, as much for conventional aircraft, whose performance must be enhanced to meet new societal requirements in terms of economy, noise (particularly during landing), vortex production near runways, etc., as for high-capacity or supersonic aircraft of the future. Our implication concerns shape optimization of wings or simplified configurations.

Our current involvement with Space applications relates to software platforms for code coupling.

4.2. Mechanical industry

A new application domain related to the parameter and shape optimization of mechanical structures is under active development. The mechanical models range from linear elasticity of 2D or 3D structures, or thin shells, to nonlinear elastoplasticity and structural dynamics. The criteria under consideration are multiple: formability, stiffness, rupture, fatigue, crash, and so on. The design variables are the thickness and shape, and possibly the topology, of the structures. The applications are performed in collaboration with world-leading industrials, and involve the optimization of the stamping process (Blank Force, Die and Tools shapes) of High Performance steel structures as well as the optimal design of structures used for packaging purposes (cans and sprays under high pressure). Our main contribution relies on providing original and efficient algorithms to capture Pareto fronts, using smart metamodeling, and to apply game theory approaches and algorithms to propose stable compromise solutions (e.g. Nash equilibria).

4.3. Electromagnetics

In the context of shape optimization of antennas, we can split the existing results in two parts: the two-dimensional modeling concerning only the specific transverse mode TE or TM, and treatments of the real physical 3-D propagation accounting for no particular symmetry, whose objective is to optimize and identify real objects such as antennas.

Most of the numerical literature in shape optimization in electromagnetics belongs to the first part and makes intensive use of the 2-D solvers based on the specific 2-D Green kernels. The 2-D approach for the optimization of directivity led recently to serious errors due to the modeling defect. There is definitely little hope for extending the 2-D algorithms to real situations. Our approach relies on a full analysis in unbounded domains of shape sensitivity analysis for the Maxwell equations (in the time-dependent or harmonic formulation), in particular, by using the integral formulation and the variations of the Colton and Kreiss isomorphism. The use of the France Telecom software SR3D enables us to directly implement our shape sensitivity analysis in the harmonic approach. This technique makes it possible, with an adequate interpolation, to retrieve the shape derivatives from the physical vector fields in the time evolution processes involving initial impulses, such as radar or tomography devices, etc. Our approach is complementary to the “automatic differentiation codes” which are also very powerful in many areas of computational sciences. In Electromagnetics, the analysis of hyperbolic equations requires a sound treatment and a clear understanding of the influence of space approximation.

4.4. Biology and medicine

A particular effort is made to apply our expertise in solid and fluid mechanics, shape and topology design, multidisciplinary optimization by game strategies to biology and medicine. Two selected applications are privileged: solid tumors and wound healing.
Opale’s objective is to push further the investigation of these applications, from a mathematical-theoretical viewpoint and from a computational and software development viewpoint as well. These studies are led in collaboration with biologists, as well as image processing specialists.

4.5. Traffic flow

The modeling and analysis of traffic phenomena can be performed at a macroscopic scale by using partial differential equations derived from fluid dynamics. Such models give a description of collective dynamics in terms of the spatial density $\rho(t, x)$ and average velocity $v(t, x)$. Continuum models have shown to be in good agreement with empirical data. Moreover, they are suitable for analytical investigations and very efficient from the numerical point of view. Finally, they contain only few variables and parameters and they can be very versatile in order to describe different situations encountered in practice.

Opale’s research focuses on the study of macroscopic models of vehicular and pedestrian traffic, and how optimal control approaches can be used in traffic management. The project opens new perspectives of interdisciplinary collaborations on urban planning and crowd dynamics analysis.

4.6. Multidisciplinary couplings

Our expertise in theoretical and numerical modeling, in particular in relation to approximation schemes, and multilevel, multi-scale computational algorithms, allows us to envisage to contribute to integrated projects focused on disciplines other than, or coupled with fluid dynamics, such as structural mechanics, electromagnetics, biology and virtual reality, image processing, etc in collaboration with specialists of these fields. Part of this research is conducted in collaboration with ONERA.
4. Application Domains

4.1. Introduction

We are concerned with all application domains where linear wave problems arise: acoustics and elastodynamics (including fluid-structure interactions), electromagnetism and optics, and gravity water waves. We give in the sequel some details on each domain, pointing out our main motivations and collaborations.

4.2. Acoustics

As the acoustic propagation in a fluid at rest can be described by a scalar equation, it is generally considered by applied mathematicians as a simple preliminary step for more complicated (vectorial) models. However, several difficult questions concerning coupling problems have occupied our attention recently. Aeroacoustics, or more precisely, acoustic propagation in a moving compressible fluid, is for our team a new and very challenging topic, which gives rise to a lot of open questions, from the modeling (Euler equations, Galbrun equations) to the numerical approximation of such models (which poses new difficulties). Our works in this area are partially supported by EADS and Airbus. The typical objective is to reduce the noise radiated by Airbus planes. Vibroacoustics, which concerns the interaction between sound propagation and vibrations of thin structures, also raises up a lot of relevant research subjects.

Both applications (Aeroacoustics and Vibroacoustics) led us in particular to develop an academic research between volume methods and integral equations in time domain.

Finally, a particularly attractive application concerns the simulation of musical instruments, whose objectives are both a better understanding of the behavior of existing instruments and an aid for the manufacturing of new instruments. The modeling and simulation of the timpani and of the guitar have been carried out in collaboration with A. Chaigne of ENSTA. We are currently on the piano.

4.3. Electromagnetism

This is a particularly important domain, first because of the very important technological applications but also because the treatment of Maxwell’s equations is much more technically involved from the mathematical point of view that the scalar wave equation. Applied mathematics for electromagnetism during the last ten years have mainly concerned stealth technology, electromagnetic compatibility, design of optoelectronic micro-components or smart materials. Stealth technology relies in particular on the conception and simulation of new absorbing materials (anisotropic, chiral, non-linear...). The simulation of antennas raises delicate questions related to the complexity of the geometry (in particular the presence of edges and corners). In optics, the development of the Mmcr and nano optics has made recently fantastic progress and the thematic of metamaterials (with negative index of refraction) opens new amazing applications. For all these reasons, we are developing an intense research in the following areas

- Highly accurate and hybrid numerical methods in collaboration with CEA (Gramat) and ONERA (Toulouse).
- Electromagnetic wave propagation in periodic media.
- Development of simplified approximate models by asymptotic analysis for various applications: boundary layers, thin coatings, thin domains, thin wires and cables, ...
- Mathematical and numerical questions linked to the modeling of metamaterials.
4.4. Elastodynamics

Wave propagation in solids is with no doubt, among the three fundamental domains that are acoustics, electromagnetism and elastodynamics, the one that poses the most significant difficulties from mathematical and numerical points of view.

Our activity on this topic began with applications in geophysics, which unfortunately has been forced to slow down in the middle of the 90’s due to the disengagement of French oil companies in matter of research. However it has seen a most welcomed rebound through new academic problems (in particular surface waves, perfectly matched layers techniques, inverse problems in wave guides) and industrial contacts, more precisely with CEA-LIST with which we have developed a long term collaboration in the domain of non destructive testing by ultrasounds. The most recent problems we have been dealing with in this domain concern elastic wave propagation in plates, the modeling of piezoelectric devices or elastic wave propagation in highly heterogeneous media.
PUMAS Team (section vide)
SIMPAF Project-Team (section vide)
4. Application Domains

4.1. Panorama

About 15 years ago, working on the physics of detonation waves in highly energetic materials, we discovered a domain where flow conditions were extreme. Numerical simulations in detonation conditions were a true challenge. The mathematical models as well as numerical methods must be particularly well built. The presence of material interfaces was posing considerable difficulties.

During the years 90–95, we have investigated open and classified litterature in the domain of multimaterial shock-detonation physics codes. We came to the conclusion that nothing was clear regarding mixture cells. These mixture cells are a consequence of the numerical diffusion or cell projection of flow variables at contact discontinuities.

Thus, we have developed our own approach. On the basis of multiphase flow theory, revisited for a correct treatment of wave dynamics, we have proposed to solve mixture cells as true multiphase mixtures. These mixtures, initially out of equilibrium, were going to relax to mechanical equilibrium with a single pressure and velocity.

From this starting point, many extensions have been done, most times initiated by applications connected to the Defense domain. Collaborations have never stopped with these specialized laboratories since 1993. Applications have also been done with Space, Automotive, Oil, Nuclear engineering domains. International projects have started with the US and Korea.

From the technology developed in the Defense area, important applications are now coming for Space industry (CNES and SNECMA). The aim is to restart the Ariane cryogenic engine several times, for orbit change. Restarting a cryogenic engine is very challenging as the temperature difference between cryogenic liquid and walls is about 300K. Stiff phase change, cavitation, flashing in ducts and turbopumps are expected. These phenomena have to be particularly well computed as it is very important to determine the state of the fluids at the injection chamber. This is crucial for the engine ignition and combustion stability.

From a modelling point of view, our models and methods are aimed to replace the technology owned by space laboratories, taken 10 years ago from nuclear laboratories.

To deal with these industrial relations, the startup RS2N has been created in 2004 on the basis of the Innovation Law of the Minister Claude Allègre.
4. Application Domains

4.1. Panorama

Automatic Differentiation of programs gives sensitivities or gradients, that are useful for many types of applications:

- optimum shape design under constraints, multidisciplinary optimization, and more generally any algorithm based on local linearization,
- inverse problems, such as parameter estimation and in particular 4Dvar data assimilation in climate sciences (meteorology, oceanography),
- first-order linearization of complex systems, or higher-order simulations, yielding reduced models for simulation of complex systems around a given state,
- mesh adaptation and mesh optimization with gradients or adjoints,
- equation solving with the Newton method,
- sensitivity analysis, propagation of truncation errors.

4.2. Multidisciplinary optimization

A CFD program computes the flow around a shape, starting from a number of inputs that define the shape and other parameters. From this flow, it computes an optimization criterion, such as the lift of an aircraft. To optimize the criterion by a gradient descent, one needs the gradient of the output criterion with respect to all the inputs, and possibly additional gradients when there are constraints. The reverse mode of AD is a promising way to compute these gradients.

4.3. Inverse problems and Data Assimilation

Inverse problems aim at estimating the value of hidden parameters from other measurable values, that depend on the hidden parameters through a system of equations. For example, the hidden parameter might be the shape of the ocean floor, and the measurable values the altitude and speed of the surface.

One particular case of inverse problems is data assimilation [28] in weather forecasting or in oceanography. The quality of the initial state of the simulation conditions the quality of the prediction. But this initial state is largely unknown. Only some measures at arbitrary places and times are available. A good initial state is found by solving a least squares problem between the measures and a guessed initial state which itself must verify the equations of meteorology. This boils down to solving an adjoint problem, which can be done though AD [31]. Figure 1 shows an example of a data assimilation exercise using the oceanography code OPA [29] and its AD adjoint code produced by TAPENADE.

The special case of 4Dvar data assimilation is particularly challenging. The 4th dimension in “4D” is time, as available measures are distributed over a given assimilation period. Therefore the least squares mechanism must be applied to a simulation over time that follows the time evolution model. This process gives a much better estimation of the initial state, because both position and time of measurements are taken into account. On the other hand, the adjoint problem involved grows in complexity, because it must run (backwards) over many time steps. This demanding application of AD justifies our efforts in reducing the runtime and memory costs of AD adjoint codes.
Figure 1. Twin experiment using the adjoint of OPA. We add random noise to a simulation of the ocean state around the Antarctic, and we remove this noise by minimizing the discrepancy with the physical model.
4.4. Linearization

Simulating a complex system often requires solving a system of Partial Differential Equations. This is sometimes too expensive, in particular in the context of real time. When one wants to simulate the reaction of this complex system to small perturbations around a fixed set of parameters, there is a very efficient approximate solution: just suppose that the system is linear in a small neighborhood of the current set of parameters. The reaction of the system is thus approximated by a simple product of the variation of the parameters with the Jacobian matrix of the system. This Jacobian matrix can be obtained by AD. This is especially cheap when the Jacobian matrix is sparse. The simulation can be improved further by introducing higher-order derivatives, such as Taylor expansions, which can also be computed through AD. The result is often called a reduced model.

4.5. Mesh adaptation

Some approximation errors can be expressed by an adjoint state. Mesh adaptation can benefit from this. The classical optimization step can give an optimization direction not only for the control parameters, but also for the approximation parameters, and in particular the mesh geometry. The ultimate goal is to obtain optimal control parameters up to a precision prescribed in advance.
4. Application Domains

4.1. Geometric inverse problems for elliptic partial differential equations

**Participants:** Laurent Baratchart, Sylvain Chevillard, Maureen Clerc [EPI Athena], Yannick Fischer [Until November], Juliette Leblond, Ana-Maria Nicu, Théo Papadopoulos [EPI Athena].

This domain is mostly connected to the techniques described in section 3.1.

We are mainly concerned with classical inverse problems like the one of localizing defaults (as cracks, pointwise sources or occlusions) in a two or three dimensional domain from boundary data (which may correspond to thermal, electrical, or magnetic measurements), of a solution to Laplace or to some conductivity equation in the domain. These defaults can be expressed as a lack of analyticity of the solution of the associated Dirichlet-Neumann problem that may be approached, in balls, using techniques of best rational or meromorphic approximation on the boundary of the object (see section 3.1).

Actually, it turns out that traces of the boundary data on 2-D cross sections (disks) coincide with analytic functions in the slicing plane, that has branched singularities inside the disk [7]. These singularities are related to the actual location of the sources (namely, they reach in turn a maximum in modulus when the plane contains one of the sources). Hence, we are back to the 2-D framework where approximately recovering these singularities can be performed using best rational approximation.

In this connection, the realistic case where data are available on part of the boundary only offers a typical opportunity to apply the analytic extension techniques (see section 3.1.1) to Cauchy type issues, a somewhat different kind of inverse problems in which the team is strongly interested.

The approach proposed here consists in recovering, from measured data on a subset $K$ of the boundary $\partial D$ of a domain $D$ of $\mathbb{R}^2$ or $\mathbb{R}^3$, say the values $F_K$ on $K$ of some function $F$, the subset $\gamma \subset D$ of its singularities (typically, a crack or a discrete set of pointwise sources), provided that $F$ is an analytic function in $D \setminus \gamma$.

- The analytic approximation techniques (section 3.1.1) first allow us to extend $F$ from the given data $F_K$ to all of $\partial D$, if $K \neq \partial D$, which is a Cauchy type issue for which our algorithms provide robust solutions, in plane domains (see [2] for 3D spherical situations, also discussed in section 6.2).

- From these extended data on the whole boundary, one can obtain information on the presence and location of $\gamma$, using rational or meromorphic approximation on the boundary (section 3.1). This may be viewed as a discretization of $\gamma$ by the poles of the approximants [6].

This is the case in dimension 2, using classical links between analyticity and harmonicity [4], but also in dimension 3, at least in spherical or ellipsoidal domains, working on 2-D plane sections, [7].

The previous two steps were shown to provide a robust way of locating sources from incomplete boundary data in a 2-D situation with several annular layers. Numerical experiments have already yielded excellent results in 3-D situations and we are now on the way to process real experimental magneto-encephalographic data, see also sections 5.7 and 6.2.2. The PhD thesis of A.-M. Nicu is concerned with these applications, see [30], in collaboration with the Athena team of Inria Sophia Antipolis, and with neuroscience teams in partner-hospitals (hosp. Timone, Marseille).
Such methods are currently being generalized to problems with variable conductivity governed by a 2-D conjugate-Beltrami equation, see [8], [21]. The application we have in mind is to plasma confinement for thermonuclear fusion in a Tokamak, more precisely with the extrapolation of magnetic data on the boundary of the chamber from the outer boundary of the plasma, which is a level curve for the poloidal flux solving the original div-grad equation. Solving this inverse problem of Bernoulli type is of importance to determine the appropriate boundary conditions to be applied to the chamber in order to shape the plasma [53]. These issues are the topics of the PhD theses of S. Chaabi and Y. Fischer [17], and of a joint collaboration with the CEA-IRFM (Cadarache), the Laboratoire J.-A. Dieudonné at the Univ. of Nice-SA, and the CMI-LATP at the Univ. of Marseille I (see section 6.2.3).

Inverse potential problems are also naturally encountered in magnetization issues that arise in nondestructive control. A particular application, which is the object of a joint NSF-supported project with Vanderbilt University and MIT, is to geophysics where the remanent magnetization of a rock is to be analyzed using a squid-magnetometer in order to analyze the rock history; specifically, the analysis of Martian rocks is conducted at MIT, for instance to understand if inversions of the magnetic field took place there. Mathematically speaking, the problem is to recover the (3-D valued) magnetization $m$ from measurements of the vector potential:

$$\int_\Omega \frac{\text{div } m(x')}{|x-x'|} \, dx',$$

outside the volume $\Omega$ of the object.

It turns out that discretization issues in geophysics can also be approached by these approximation techniques. Namely, in geodesy or for GPS computations, one may need to get a best discrete approximation of the gravitational potential on the Earth’s surface, from partial data collected there. This is also the topic of the PhD theses of A.-M. Nicu, and of a beginning collaboration with a physicist colleague (IGN, LAREG, geodesy). Related geometrical issues (finding out the geoid, level surface of the gravitational potential) are worthy of consideration as well.

### 4.2. Identification and design of resonant systems: hyperfrequency filter identification

**Participants:** Laurent Baratchart, Stéphane Bila [XLim, Limoges], Sylvain Chevillard, José Grimm, Jean-Paul Marmorat, Martine Olivi, Fabien Seyfert.

This domain is mostly connected to the techniques described in section 3.1.

One of the best training grounds for the research of the team in function theory is the identification and design of physical systems for which the linearity assumption works well in the considered range of frequency, and whose specifications are made in the frequency domain. Resonant systems, either acoustic or electromagnetic based, are prototypical devices of common use in telecommunications.

In the domain of space telecommunications (satellite transmissions), constraints specific to onboard technology lead to the use of filters with resonant cavities in the microwave range. These filters serve multiplexing purposes (before or after amplification), and consist of a sequence of cylindrical hollow bodies, magnetically coupled by irises (orthogonal double slits). The electromagnetic wave that traverses the cavities satisfies the Maxwell equations, forcing the tangent electrical field along the body of the cavity to be zero. A deeper study (of the Helmholtz equation) states that essentially only a discrete set of wave vectors is selected. In the considered range of frequency, the electrical field in each cavity can be seen as being decomposed along two orthogonal modes, perpendicular to the axis of the cavity (other modes are far off in the frequency domain, and their influence can be neglected).
Each cavity (see Figure 1) has three screws, horizontal, vertical and midway (horizontal and vertical are two arbitrary directions, the third direction makes an angle of 45 or 135 degrees, the easy case is when all cavities show the same orientation, and when the directions of the irises are the same, as well as the input and output slits). Since the screws are conductors, they act more or less as capacitors; besides, the electrical field on the surface has to be zero, which modifies the boundary conditions of one of the two modes (for the other mode, the electrical field is zero hence it is not influenced by the screw), the third screw acts as a coupling between the two modes. The effect of the iris is to the contrary of a screw: no condition is imposed where there is a hole, which results in a coupling between two horizontal (or two vertical) modes of adjacent cavities (in fact the iris is the union of two rectangles, the important parameter being their width). The design of a filter consists in finding the size of each cavity, and the width of each iris. Subsequently, the filter can be constructed and tuned by adjusting the screws. Finally, the screws are glued. In what follows, we shall consider a typical example, a filter designed by the CNES in Toulouse, with four cavities near 11 Ghz.

Near the resonance frequency, a good approximation of the Maxwell equations is given by the solution of a second order differential equation. One obtains thus an electrical model for our filter as a sequence of electrically-coupled resonant circuits, and each circuit will be modeled by two resonators, one per mode, whose resonance frequency represents the frequency of a mode, and whose resistance represent the electric losses (current on the surface).

In this way, the filter can be seen as a quadripole, with two ports, when plugged on a resistor at one end and fed with some potential at the other end. We are then interested in the power which is transmitted and reflected. This leads to defining a scattering matrix $S$, that can be considered as the transfer function of a stable causal linear dynamical system, with two inputs and two outputs. Its diagonal terms $S_{1,1}$, $S_{2,2}$ correspond to reflections at each port, while $S_{1,2}$, $S_{2,1}$ correspond to transmission. These functions can be measured at certain frequencies (on the imaginary axis). The filter is rational of order 4 times the number of cavities (that is 16 in the example), and the key step consists in expressing the components of the equivalent electrical circuit as a function of the $S_{ij}$ (since there are no formulas expressing the lengths of the screws in terms of parameters.
of this electrical model). This representation is also useful to analyze the numerical simulations of the Maxwell equations, and to check the design, particularly the absence of higher resonant modes.

In fact, resonance is not studied via the electrical model, but via a low-pass equivalent circuit obtained upon linearizing near the central frequency, which is no longer conjugate symmetric (i.e., the underlying system may not have real coefficients) but whose degree is divided by 2 (8 in the example).

In short, the identification strategy is as follows:

- measuring the scattering matrix of the filter near the optimal frequency over twice the pass band (which is 80MHz in the example).
- solving bounded extremal problems for the transmission and the reflection (the modulus of the response being respectively close to 0 and 1 outside the interval measurement, cf. section 3.1.1). This provides us with a scattering matrix of order roughly 1/4 of the number of data points.
- Approximating this scattering matrix by a rational transfer-function of fixed degree (8 in this example) via the Endymion or RARL2 software (cf. section 3.1.4).
- A realization of the transfer function is thus obtained, and some additional symmetry constraints are imposed.
- Finally one builds a realization of the approximant and looks for a change of variables that eliminates non-physical couplings. This is obtained by using algebraic-solvers and continuation algorithms on the group of orthogonal complex matrices (symmetry forces this type of transformation).

The final approximation is of high quality. This can be interpreted as a validation of the linearity hypothesis for the system: the relative $L^2$ error is less than $10^{-3}$. This is illustrated by a reflection diagram (Figure 2). Non-physical couplings are less than $10^{-2}$.

The above considerations are valid for a large class of filters. These developments have also been used for the design of non-symmetric filters, useful for the synthesis of repeating devices.

The team currently investigates the design of output multiplexors (OMUX) where several filters of the previous type are coupled on a common guide. In fact, it has undergone a rather general analysis of the question “How does an OMUX work?” With the help of numerical simulations and Schur analysis, general principles are being worked out to take into account:

- the coupling between each channel and the “Tee” that connects it to the manifold,
- the coupling between two consecutive channels.

![Figure 2. Nyquist Diagram. Rational approximation (degree 8) and data - $S_{22}$.](image)
The model is obtained upon chaining the corresponding scattering matrices and it intermingles rational elements and complex exponentials (because of the delays) hence constitutes an extension of the previous framework. Its study is being conducted under contract with Thales Alenia Space (Toulouse) (see sections 7.1).

4.3. Spatial mechanics

Participants: Ludovic Rifford, Jana Nemcova, Jean-Baptiste Pomet.

This domain is mostly related to the techniques described in section 3.2.

Generally speaking, aerospace engineering requires sophisticated control techniques for which optimization is often crucial, due to the extreme functioning conditions. The use of satellites in telecommunication networks motivates a lot of research in the area of signal and image processing; see for instance section 4.2. Of course, this requires that satellites be adequately controlled, both in position and orientation (the so-called attitude of the satellite). This problem and similar ones continue to motivate research in control. The team has been working for six years on control problems in orbital transfer with low thrust engines, including four years under contract with Thales Alenia Space (formerly Alcatel Space) in Cannes.

Technically, the reason for using these (ionic) low thrust engines, rather than chemical engines that deliver a much higher thrust, is that they require much less “fuel”; this is decisive because the total mass is limited by the capacity of the launchers: less fuel means more payload, while fuel represents today an impressive part of the total mass.

From the control point of view, the low thrust makes the transfer problem delicate. In principle of course, the control law leading to the right orbit in minimum time exists, but it is numerically involved, ill-conditioned and the computation is non-robust against many unmodelled phenomena. Considerable progress on the approximation of such a law by a feedback has been carried out using ad hoc Lyapunov functions. These approximate surprisingly well time-optimal trajectories. The easy implementation of such control laws makes them attractive as compared to genuine optimal control. Here the \( n - 1 \) first integrals are an easy means to build control Lyapunov functions since any function of these first integrals can be made monotone decreasing by a suitable control. See [54] and the references therein.
4. Application Domains

4.1. Introduction

Many systems (either actual or abstract) can be represented by \( (1) \). Some typical examples are:

- Mechanical systems with unilateral constraints and dry friction (the biped robot is a typical example), including kinematic chains with slack, phenomena of liquid slosh, etc.
- Electrical circuits with ideal diodes and/or transistors Mos.
- Optimal control with constraints on the state, closed loop of a system controlled by an MPC algorithm\(^2\), etc.

This class of models is not too large (to allow thorough studies), yet rich enough to include many applications. This goes in contrast to a study of general hybrid systems. Note for example that \( (1) \) is a “continuous” hybrid system, in that the continuous variables \( x \) and \( u \) prevail in the evolution (there is no discrete control to commute from a mode to the other: only the input \( u \) can be used). Let us cite some specific applications.

4.2. Nonsmooth mechanical systems

This constitutes a major topic of the team. Walking robots, flexible beams that model hair dynamics, circuit breakers, granular materials, structures like 2D or 3D blocks on moving grounds, are important examples of mechanical systems that involve unilateral contact with friction. Their analysis, control, simulation, modelling, require specific tools from convex or nonsmooth analysis, complementarity theory, variational inequalities theory, and impact mechanics.

4.3. Computational neuroscience

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

4.4. Electronic circuits

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

\(^2\) model predictive control
4.5. Walking robots

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

4.6. Optimization

Optimization exists in virtually all economic sectors. Simulation tools can be used to optimize the system they simulate. Another domain is parameter identification (Idopt or Estime teams), where the deviation between measurements and theoretical predictions must be minimized. Accordingly, giving an exhaustive list of applications is impossible. Some domains where Inria has been implied in the past, possibly through the former Promath and Numopt teams are: production management, geophysics, finance, molecular modeling, robotics, networks, astrophysics, crystallography, ...Our current applicative activity includes: the management of electrical production (deterministic or stochastic), the design and operation of telecommunication networks.

4.7. Computer graphics Animation

A new application in Bipop is the simulation of complex scenes involving many interacting objects. Whereas the problem of collision detection has become a mature field those recent years, simulating the collision response (in particular frictious contacts) in a realistic, robust and efficient way, still remains an important challenge. Another related issue we began to study is the simulation of heterogeneous objects such as granular or fibrous materials, which requires the design of new high-scales models for dynamics and contacts; indeed, for such large systems, simulating each interacting particle/fiber individually would be too much time-consuming for typical graphics applications. We also pursue some study on the design of high-order models for slender structures such as rods, plates or shells. Finally, our current activity includes the static inversion of mechanical objects, which is of great importance in the field of artistic design, for the making of movies and video games for example. Such problems typically involve geometric fitting and parameters identification issues, both resolved with the help of constrained optimization.
4. Application Domains

4.1. Introduction

Commands is a team with a strong commitment in tackling real-life applications in addition to theoretical challenges. This shows in our long history of contracts with industrial partners. In the recent years, we have mainly contributed to the following fields of application.

4.2. Aerospace applications

In the framework of a long-term partnership with the Cnes, and more recently Astrium, we have studied trajectory optimization for space launcher problems. This kind of problems typically involves hard constraints (thermal flux, mechanical efforts) and inexact models (atmosphere, aerodynamic forces). The two main achievements were to study when singular arcs may occur, and to show the effectiveness of a HJB approach on a reduced model. Singular arcs are flight phases with a non-maximal thrust, induced by a tradeoff between speed and atmospheric drag; they cause difficulties of both theoretical and practical nature. The latter point is the first step in the process of applying global methods to this class of difficult problems.

4.3. Trading applications

In a partnership with Total, we have studied problems dealing with the trading of Liquefied Natural Gas. We have computed maximizing revenue policies, by combining the Stochastic Dual Dynamic Programming approach (SDDP) with a quantization method for the noise that enters in prices. We have also given partial results for the case of integer decision.

4.4. Energy applications

With Renault, we have studied problems of energy management for hybrid vehicles. Hybrid vehicles include an auxiliary thermal (gas) engine that is used as a range extender for the main electric propulsion. We are interested in determining the optimal policies for energy management, taking into account some stochastic uncertainties, as well as execution delay and decision lags.
4. Application Domains

4.1. Panorama

As we already stressed in the previous sections the robust control of infinite dimensional systems is an emerging theory. Our aim is to develop tools applicable to a large class of problems which will be tested on models of increasing complexity. We describe below only the applications in which the members of our team have recently obtained important achievements.

4.2. Biology and Medicine

4.2.1. Medicine

We began this year to study a new class of applications of observability theory. The investigated issues concern inverse problems in Magnetic Resonance Imaging (MRI) of moving bodies with emphasis on cardiac MRI. The main difficulty we tackle is due to the fact that MRI is, comparatively to other cardiac imaging modalities, a slow acquisition technique, implying that the object to be imaged has to be still. This is not the case for the heart where physiological motions, such as heart beat or breathing, are of the same order of magnitude as the acquisition time of an MRI image. Therefore, the assumption of sample stability, commonly used in MRI acquisition, is not respected. The violation of this assumption generally results in flow or motion artifacts. Motion remains a limiting factor in many MRI applications, despite different approaches suggested to reduce or compensate for its effects Welch et al. [85]. Mathematically, the problem can be stated as follows: can we reconstruct a moving image by measuring at each time step a line of its Fourier transform? From a control theoretic point of view this means that we want to identify the state of a dynamical system by using an output which is a small part of its Fourier transform (this part may change during the measurement).

There are several strategies to overcome these difficulties but most of them are based on respiratory motion suppression with breath-hold. Usually MRI uses ECG information to acquire an image over multiple cardiac cycles by collecting segments of Fourier space data at the same delay in the cycle Lanzer et al. [76], assuming that cardiac position over several ECG cycles is reproducible. Unfortunately, in clinical situations many subjects are unable to hold their breath or maintain stable apnea. Therefore breath-holding acquisition techniques are limited in some clinical situations. Another approach, so called real-time, uses fast, but low resolution sequences to be faster than heart motion. But these sequences are limited in resolution and improper for diagnostic situations, which require small structure depiction as for coronary arteries.

4.3. Simulation of viscous fluid-structure interactions

Participants: Bruno Pinçon, Jean-François Scheid [correspondant].

A number of numerical codes for the simulation for fluids and fluid-structure problems has been developed by the team. These codes are mainly written in MATLAB Software with the use of C++ functions in order to improve the sparse array process of MATLAB. We have focused our attention on 3D simulations which require large CPU time resources as well as large memory storage. An efficient 3D Stokes sparse solver for MATLAB is now available. An important work has been performed for the study and the development of a class of preconditioners for iterative solver of 3D Stokes problem. Efficient preconditioner of block preconditioned conjugate gradient type (BPCG) is now implemented. The use of this preconditioner significantly reduces the CPU time for the solution of linear system coming from the Stokes equations. This work has been developed in collaboration with Marc Fuentes, research engineer at INRIA Nancy Grand Est. M. Fuentes has also written a PYTHON version of the 3D Stokes solver. A 3D characteristics method for the nonlinear Navier-Stokes equations is now in progress.
4.4. Biohydrodynamics MATLAB Toolbox (BHT)

Participants: Alexandre Munnier [correspondant], Bruno Pinçon.

Understanding the locomotion of aquatic animals fascinated the scientific community for a long time. This constant interest has grown from the observation that aquatic mammals and fishes evolved swimming capabilities superior to what has been achieved by naval technology. A better understanding of the biomechanics of swimming may allow one to improve the efficiency, manoeuvrability and stealth of underwater vehicles. During the last fifty years, several mathematical models have been developed. These models make possible the qualitative analysis of swimming propulsion as a continuation of the previously developed quantitative theories. Based on recent mathematical advances, Biohydrodynamics MATLAB Toolbox (BHT) is a collection of M-Files for design, simulation and analysis of articulated bodies’ motions in fluid. More widely, BHT allows also to perform easily any kind of numeric experiments addressing the motion of solids in ideal fluids (simulations of so-called fluid-structure interaction systems).

This software is available at http://bht.gforge.inria.fr/ .
4. Application Domains

4.1. Modeling and analysis of Acute Myeloid Leukemia

In collaboration with the BANG project-team at INRIA Paris-Rocquencourt, the DRACULA team at INRIA Grenoble - Rhône-Alpes, the COMMANDS project team at INRIA Saclay-Île-de-France, INSERM, Cordeliers Research Center and St Antoine Hospital, Paris, we consider the modeling and control of Acute Myeloid Leukemia (AML).

The main goal of this project is the theoretical optimization of drug treatments used in AML, with experimental validation in cell cultures, aiming at proposing efficient therapeutic strategies in clinic.

We work on a discrete maturity-structured model of hematopoiesis introduced in [98]. In this model, several generations of cells are considered and, for the first time, the cell cycle duration is assumed to be distributed. At each level, the population of immature cells are divided into two subpopulations: proliferating and non proliferating cells. Physiological phenomena of re-introduction from the non proliferative into the proliferative subpopulation is modeled in the team as a nonlinear dynamical interconnection between the two sub-populations, and input-output tools seem to be useful in this context [35].

4.2. Control of continuous bioreactors

We study problems of coexistence or regulation of species of micro-organisms in bio-reactors called chemostats.

In [37], we have studied a competition model between an arbitrary number of species in a chemostat with one limiting substrate and including both monotone and non-monotone growth functions, distinct removal rates and variable yields. The dilution rate and the substrate input concentration were chosen as positive constants. We have shown that only the species with the lowest break-even concentration survives, provided that additional technical conditions on the growth functions and yields are satisfied. The proof relies on the construction of a Lyapunov function.

In [62], we studied chemostat models in which the species compete for two or more limiting substrates. First we considered the case where the nutrient flow and species removal rates and input nutrient concentrations are all given positive constants. In that case, we use Brouwer degree theory to give conditions guaranteeing that the models admit globally asymptotically stable componentwise positive equilibrium points, from all componentwise positive initial states. Then we used the results to develop stabilization theory for controlled chemostats with two or more limiting nutrients. For cases where the dilution rate and input nutrient concentrations can be selected as controls, we prove that many different componentwise positive equilibria can be made globally asymptotically stable. This significantly extends the existing control results for chemostats with one limiting nutrient. We demonstrate our methods in simulations.

4.3. PVTOL Aircraft

In [20] and [51], we applied the technique of backstepping and of construction of strict Lyapunov functions to solve a tracking problem for the celebrated aircraft model PVTOL (Planar Vertical Takeoff and Landing). It is a benchmark dynamics for an aircraft moving in a vertical plane that contains the important features needed to design controllers for real aircraft. The controllers are the thrust out of the bottom and the rolling moment controller. The main challenges are that the thrust controller must remain nonnegative and that the system is underactuated. We overcame these challenges through a change of variables that transforms the PVTOL tracking dynamics into a chain of three subsystems and then applying asymptotic strict Lyapunov functions and bounded backstepping. Relative to the PVTOL model literature, the significance of our PVTOL work was (a) the global boundedness of our controllers in the decoupled coordinates, (b) their applicability to
cases where the velocity measurements are not available, by using an observer, (c) the positive lower bound on the thrust controller, (d) our allowing a very general class of reference trajectories, and (e) our use of ISS to certify good performance under actuator errors, which would not be possible using LaSalle invariance or nonstrict Lyapunov functions.
4. Application Domains

4.1. Quantum control

The issue of designing efficient transfers between different atomic or molecular levels is crucial in atomic and molecular physics, in particular because of its importance in those fields such as photochemistry (control by laser pulses of chemical reactions), nuclear magnetic resonance (NMR, control by a magnetic field of spin dynamics) and, on a more distant time horizon, the strategic domain of quantum computing. This last application explicitly relies on the design of quantum gates, each of them being, in essence, an open loop control law devoted to a prescribed simultaneous control action. NMR is one of the most promising techniques for the implementation of a quantum computer.

Physically, the control action is realized by exciting the quantum system by means of one or several external fields, being them magnetic or electric fields. The resulting control problem has attracted increasing attention, especially among quantum physicists and chemists (see, for instance, [78], [84]). The rapid evolution of the domain is driven by a multitude of experiments getting more and more precise and complex (see the recent review [37]). Control strategies have been proposed and implemented, both on numerical simulations and on physical systems, but there is still a large gap to fill before getting a complete picture of the control properties of quantum systems. Control techniques should necessarily be innovative, in order to take into account the physical peculiarities of the model and the specific experimental constraints.

The area where the picture got clearer is given by finite dimensional linear closed models.

- **Finite dimensional** refers to the dimension of the space of wave functions, and, accordingly, to the finite number of energy levels.
- **Linear** means that the evolution of the system for a fixed (constant in time) value of the control is determined by a linear vector field.
- **Closed** refers to the fact that the systems are assumed to be totally disconnected from the environment, resulting in the conservation of the norm of the wave function.

The resulting model is well suited for describing spin systems and also arises naturally when infinite dimensional quantum systems of the type discussed below are replaced by their finite dimensional Galerkin approximations. Without seeking exhaustiveness, let us mention some of the issues that have been tackled for finite dimensional linear closed quantum systems:

- controllability [19],
- bounds on the controllability time [15],
- STIRAP processes [89],
- simultaneous control [61],
- optimal control ([57], [28], [39]),
- numerical simulations [67].

Several of these results use suitable transformations or approximations (for instance the so-called rotating wave) to reformulate the finite-dimensional Schrödinger equation as a sub-Riemannian system. Open systems have also been the object of an intensive research activity (see, for instance, [20], [58], [79], [34]).
In the case where the state space is infinite dimensional, some optimal control results are known (see, for instance, [24], [35], [54], [25]). The controllability issue is less understood than in the finite dimensional setting, but several advances should be mentioned. First of all, it is known that one cannot expect exact controllability on the whole Hilbert sphere [88]. Moreover, it has been shown that a relevant model, the quantum oscillator, is not even approximately controllable [80], [70]. These negative results have been more recently completed by positive ones. In [26], [27] Beauchard and Coron obtained the first positive controllability result for a quantum particle in a 1D potential well. The result is highly nontrivial and is based on Coron’s return method (see [43]). Exact controllability is proven to hold among regular enough wave functions. In particular, exact controllability among eigenfunctions of the uncontrolled Schrödinger operator can be achieved. Other important approximate controllability results have then been proved using Lyapunov methods [69], [74], [55]. While [69] studies a controlled Schrödinger equation in $\mathbb{R}$ for which the uncontrolled Schrödinger operator has mixed spectrum, [74], [55] deal mainly with general discrete-spectrum Schrödinger operators.

In all the positive results recalled in the previous paragraph, the quantum system is steered by a single external field. Different techniques can be applied in the case of two or more external fields, leading to additional controllability results [46], [31].

The picture is even less clear for nonlinear models, such as Gross–Pitaevski and Hartree–Fock equations. The obstructions to exact controllability, similar to the ones mentioned in the linear case, have been discussed in [52]. Optimal control approaches have also been considered [23], [36]. A comprehensive controllability analysis of such models is probably a long way away.

### 4.2. Neurophysiology

At the interface between neurosciences, mathematics, automatics and humanoid robotics, an entire new approach to neurophysiology is emerging. It arouses a strong interest in the four communities and its development requires a joint effort and the sharing of complementary tools.

A family of extremely interesting problems concerns the understanding of the mechanisms supervising some sensorial reactions or biomechanics actions such as image reconstruction by the primary visual cortex, eyes movement and body motion.

In order to study these phenomena, a promising approach consists in identifying the motion planning problems undertaken by the brain, through the analysis of the strategies that it applies when challenged by external inputs. The role of control is that of a language allowing to read and model neurological phenomena. The control algorithms would shed new light on the brain’s geometric perception (the so-called neurogeometry [76]) and on the functional organization of the motor pathways.

- A challenging problem is that of the understanding of the mechanisms which are responsible for the process of image reconstruction in the primary visual cortex V1.

The visual cortex areas composing V1 are notable for their complex spatial organization and their functional diversity. Understanding and describing their architecture requires sophisticated modeling tools. At the same time, the structure of the natural and artificial images used in visual psychophysics can be fully disclosed only using rather deep geometric concepts. The word “geometry” refers here to the internal geometry of the functional architecture of visual cortex areas (not to the geometry of the Euclidean external space). Differential geometry and analysis both play a fundamental role in the description of the structural characteristics of visual perception.

A model of human perception based on a simplified description of the visual cortex V1, involving geometric objects typical of control theory and sub-Riemannian geometry, has been first proposed by Petitot ([77]) and then modified by Citti and Sarti ([42]). The model is based on experimental observations, and in particular on the fundamental work by Hubel and Wiesel [51] who received the Nobel prize in 1981.
In this model, neurons of V1 are grouped into orientation columns, each of them being sensitive to visual stimuli arriving at a given point of the retina and oriented along a given direction. The retina is modeled by the real plane, while the directions at a given point are modeled by the projective line. The fiber bundle having as base the real plane and as fiber the projective line is called the bundle of directions of the plane.

From the neurological point of view, orientation columns are in turn grouped into hypercolumns, each of them sensitive to stimuli arriving at a given point, oriented along any direction. In the same hypercolumn, relative to a point of the plane, we also find neurons that are sensitive to other stimuli properties, such as colors. Therefore, in this model the visual cortex treats an image not as a planar object, but as a set of points in the bundle of directions of the plane. The reconstruction is then realized by minimizing the energy necessary to activate orientation columns among those which are not activated directly by the image. This gives rise to a sub-Riemannian problem on the bundle of directions of the plane.

Another class of challenging problems concern the functional organization of the motor pathways.

The interest in establishing a model of the motor pathways, at the same time mathematically rigorous and biologically plausible, comes from the possible spillovers in neurophysiology. It could help to design better control strategies for robots and artificial limbs, rendering them capable to move more progressively and smoothly and also to react to exterior perturbations in a flexible way. An underlying relevant societal goal (clearly beyond our domain of expertise) is to clarify the mechanisms of certain debilitating troubles such as cerebellar disease, chorea and Parkinson's disease.

A key issue in order to establish a model of the motor pathways is to determine the criteria underlying the brain's choices. For instance, for the problem of human locomotion (see [22]), identifying such criteria would be crucial to understand the neural pathways implicated in the generation of locomotion trajectories.

A nowadays widely accepted paradigm is that, among all possible movements, the accomplished ones satisfy suitable optimality criteria (see [87] for a review). One is then led to study an inverse optimal control problem: starting from a database of experimentally recorded movements, identify a cost function such that the corresponding optimal solutions are compatible with the observed behaviors.

Different methods have been taken into account in the literature to tackle this kind of problems, for instance in the linear quadratic case [56] or for Markov processes [75]. However all these methods have been conceived for very specific systems and they are not suitable in the general case. Two approaches are possible to overcome this difficulty. The direct approach consists in choosing a cost function among a class of functions naturally adapted to the dynamics (such as energy functions) and to compare the solutions of the corresponding optimal control problem to the experimental data. In particular one needs to compute, numerically or analytically, the optimal trajectories and to choose suitable criteria (quantitative and qualitative) for the comparison with observed trajectories. The inverse approach consists in deriving the cost function from the qualitative analysis of the data.

4.3. Switched systems

Switched systems form a subclass of hybrid systems, which themselves constitute a key growth area in automation and communication technologies with a broad range of applications. Existing and emerging areas include automotive and transportation industry, energy management and factory automation. The notion of hybrid systems provides a framework adapted to the description of the heterogeneous aspects related to the interaction of continuous dynamics (physical system) and discrete/logical components.

The characterizing feature of switched systems is the collective aspect of the dynamics. A typical question is that of stability, in which one wants to determine whether a dynamical system whose evolution is influenced by a time-dependent signal is uniformly stable with respect to all signals in a fixed class ([63]).
The theory of finite-dimensional hybrid and switched systems has been the subject of intensive research in the last decade and a large number of diverse and challenging problems such as stabilizability, observability, optimal control and synchronization have been investigated (see for instance [85], [64]).

The question of stability, in particular, because of its relevance for applications, has spurred a rich literature. Important contributions concern the notion of common Lyapunov function: when there exists a Lyapunov function that decays along all possible modes of the system (that is, for every possible constant value of the signal), then the system is uniformly asymptotically stable. Conversely, if the system is stable uniformly with respect to all signals switching in an arbitrary way, then a common Lyapunov function exists [65]. In the linear finite-dimensional case, the existence of a common Lyapunov function is actually equivalent to the global uniform exponential stability of the system [71] and, provided that the admissible modes are finitely many, the Lyapunov function can be taken polyhedral or polynomial [29], [30], [44]. A special role in the switched control literature has been played by common quadratic Lyapunov functions, since their existence can be tested rather efficiently (see [45] and references therein). Algebraic approaches to prove the stability of switched systems under arbitrary switching, not relying on Lyapunov techniques, have been proposed in [62], [16].

Other interesting issues concerning the stability of switched systems arise when, instead of considering arbitrary switching, one restricts the class of admissible signals, by imposing, for instance, a dwell time constraint [50].

Another rich area of research concerns discrete-time switched systems, where new intriguing phenomena appear, preventing the algebraic characterization of stability even for small dimensions of the state space [59]. It is known that, in this context, stability cannot be tested on periodic signals alone [32].

Finally, let us mention that little is known about infinite-dimensional switched system, with the exception of some results on uniform asymptotic stability ([68], [82], [83]) and some recent papers on optimal control ([49], [90]).
MAXPLUS Project-Team

4. Application Domains

4.1. Systèmes à événements discrets (productique, réseaux)/Discrete event systems (manufacturing systems, networks)

One important part of applications of max-plus algebra comes from discrete event dynamical systems [6]. Max-plus linear systems, and more generally, monotone nonexpansive dynamical systems, provide natural models for which many analytical results can be applied to performance evaluation problems. For instance, problems like computing the cycle time of asynchronous digital circuits [94], or computing the throughput of a workshop [138] or of a transportation network, and performance evaluation problems for communication networks, are often amenable to max-plus algebra, at least in some simplified form, see in particular [93] and [85]. The max-plus approach has been applied to the analysis of the time behaviour of concurrent systems, and in particular, to the analysis of high level sequence message charts [89], [146]. The Maxplus team collaborates with the Metalau team, working particularly on the applications of max-plus models to the microscopic modelling of road traffic [152], [150], [119].

4.2. Commande optimale et jeux/Optimal control and games

Optimal control and game theory have numerous well established applications fields: mathematical economy and finance, stock optimization, optimization of networks, decision making, etc. In particular, the Mathfi team works on applications to problems of mathematics finances. There is a tradition of collaboration between researchers of the Maxplus team and of the Mathfi team on these questions, see as an illustration [5] where ideas from the spectral theory of monotone homogeneous maps [3] are applied.

4.3. Recherche opérationnelle/Operations research

One important part of applications of max-plus algebra comes from discrete event dynamical systems [6]. Max-plus linear systems, and more generally, monotone nonexpansive dynamical systems, provide natural models for which many analytical results can be applied to performance evaluation problems. For instance, problems like computing the cycle time of asynchronous digital circuits [94], or computing the throughput of a workshop [138] or of a transportation network, and performance evaluation problems for communication networks, are often amenable to max-plus algebra, at least in some simplified form, see in particular [93] and [85]. The max-plus approach has been applied to the analysis of the time behaviour of concurrent systems, and in particular, to the analysis of high level sequence message charts [89], [146]. The Maxplus team collaborates with the Metalau team, working particularly on the applications of max-plus models to the microscopic modelling of road traffic [152], [150], [119].
comme le problème de circuit de poids moyen maximum [104]. Certains problèmes combinatoires, comme des problèmes de programmation disjonctive, peuvent être décomposés par des méthodes de type max-plus [184]. Ensuite, le rôle de l’algèbre max-plus dans les problèmes d’ordonnancement est bien connu depuis les années 60, les dates de complétion pouvant souvent être calculées à partir d’équations linéaires max-plus. Plus récemment, des représentations de problèmes d’ordonnancement ont pu être obtenues à partir de semi-groupes de matrices max-plus : une première représentation a été obtenue dans [126] pour le cas du “jobshop”, une représentation plus simple a été obtenue dans [147] dans le cas du “flowshop”. Ce point de vue algébrique a été très utile dans le cas du “flowshop” : il permet de retrouver des résultats anciens de dominance et d’obtenir ainsi de nouvelles bornes [147]. Finalement, en regardant l’algèbre max-plus comme une limite de l’algèbre classique, on peut utiliser des outils algébriques en optimisation combinatoire [144].

**English version**

Max-plus algebra arise in several ways in Operations Research. First, there are intimate relations between max-plus algebra and discrete optimisation problems, see [95]. Sometimes, these relations lead to new algorithms for classical Operations Research problems, like the maximal circuit mean [104]. There are also special combinatorial problems, like certain problems of disjunctive programming, which can be decomposed by max-plus type methods [184]. Next, the role of max-plus algebra in scheduling problems has been known since the sixties: completion dates can often be computed by max-plus linear equations. Recently, representations of certain scheduling problems using max-plus matrix semigroups have appeared, a first representation was given in [126] for the jobshop case, a simpler representation was given in [147] in the flowshop case. This algebraic point of view turned out to be particularly fruitful in the flowshop case: it allows one to recover old dominance results and to obtain new bounds [147]. Finally, viewing max-plus algebra as a limit of classical algebra allows to use algebraic tools in combinatorial optimisation [144].

4.4. Analyse statique de programmes/Static analysis of computer programs

L’interprétation abstraite est une technique, introduite par P. et R. Cousot [108], qui permet de déterminer des invariants de programmes en calculant des points fixes minimaux d’applications monotones définies sur certains treillis. On associe en effet à chaque point de contrôle du programme un élément du treillis, qui représente une sur-approximation valide de l’ensemble des valeurs pouvant être prises par les variables du programme en ce point. Le treillis le plus simple exprimant des propriétés numériques est celui des produits Cartésiens d’intervalles. Des treillis plus riches permettent de mieux tenir compte de relations entre variables, en particulier, des classes particulières de polyédres sont souvent employées.

Voici, en guise d’illustration, un petit exemple de programme, avec le système de point fixe associé, pour le treillis des intervalles:

```c
void main() {
    int x=0;  // 1
    while (x<100) {  // 2
        x=x+1;  // 3
    }  // 4
}
```

Si l’on s’intéresse par exemple aux valeurs maximales prise par la variable $x$ au point de contrôle 2, soit $x_2^+ := \max x_2$, après une élimination, on parvient au problème de point fixe:

$$x_2^+ = \min (99, \max (0, x_2^+ + 1)) ,$$

qui a pour plus petite solution $x_2^+ = 99$, ce qui prouve que $x$ est majoré par 99 au point 2.
On reconnaît ici un opérateur de point fixe associé à un problème de jeux à deux joueurs et somme nulle. Cette analogie est en fait générale, dans le cadre d’un collaboration que l’équipe entretient depuis plusieurs années avec l’équipe MeASI d’Eric Goubault (CEA et LIX), spécialiste d’analyse statique, nous avons en effet mis progressivement en évidence une correspondance [107], [123], entre les problèmes de jeux à somme nulle et les problèmes d’analyse statique, qui peut se résumer par le dictionnaire suivant:

<table>
<thead>
<tr>
<th>Jeux</th>
<th>Interprétation abstraite</th>
</tr>
</thead>
<tbody>
<tr>
<td>système dynamique</td>
<td>programme</td>
</tr>
<tr>
<td>opérateur de Shapley</td>
<td>fonctionnelle</td>
</tr>
<tr>
<td>espace d’état</td>
<td>(# points de contrôle) x (# degrés de liberté du treillis)</td>
</tr>
<tr>
<td>problème en horizon n</td>
<td>exécution de n pas</td>
</tr>
<tr>
<td>limite du problème en horizon fini</td>
<td>invariant optimal (borne)</td>
</tr>
<tr>
<td>itération sur les valeurs</td>
<td>itération de Kleene</td>
</tr>
</tbody>
</table>

Pour que le nombre d’états du jeu soit fini, il est nécessaire de se limiter à des treillis d’ensembles ayant un nombre fini de degrés de liberté, ce qui est le cas de domaines communément utilisés (intervalles, ensembles définis par des contraintes de potentiel de type $x_i - x_j \leq \text{cst}$, mais aussi, les “templates” qui sont des sous-classes de polyèdres introduits récemment par Sankaranarayanan, Sipma et Manna [175]). L’ensemble des actions est alors fini si on se limite à une arithmétique affine. Signalons cependant qu’en toute généralité, on aboutit à des jeux avec un taux d’escompte négatif, ce qui pose des difficultés inédites. Cette correspondance entre jeux et analyse statique est non intuitive, au sens où les actions du minimiseur consistent à sélectionner des points extrêmes de certains polyèdres obtenus par un mécanisme de dualité.

Une pathologie bien répertoriée en analyse statique est la lenteur des algorithmes de point fixe, qui peuvent effectuer un nombre d’itérations considérable (99 itérations pour obtenir le plus petit point fixe de (8)). Celle-ci est usuellement traitée par des méthodes d’accélération de convergence dites d’élargissement et rétrécissement [109], qui ont cependant l’inconvénient de conduire à une perte de précision des invariants obtenus. Nous avons exploité la correspondance entre analyse statique et jeux pour développer des algorithmes d’une nature très différente, s’inspirant de nos travaux antérieurs sur l’itération sur les politiques pour les jeux répétés [124], [102], [103],[7]. Une version assez générale de cet algorithme, adaptée au domaine des templates, est décrite dans [123] et a fait l’objet d’une implémentation prototype. Chaque itération combine de la programmation linéaire et des algorithmes de graphes. Des résultats expérimentaux ont montré le caractère effectif de la méthode, avec souvent un gain en précision par rapport aux approches classiques, par exemple pour des programmes comprenant des boucles imbriquées.

Ce domaine se trouve être en pleine évolution, un enjeu actuel étant de traiter d’une manière qui passe à l’échelle des invariants plus précis, y compris dans des situations où l’arithmétique n’est plus affine.

**English version**

The abstract interpretation method introduced by P. and R. Cousot [108], allows one to determine automatically invariants of programs by computing the minimal fixed point of an order preserving map defined on a complete lattice. To every breakpoint of the program is associated an element of the lattice, which yields a valid overapproximation of the set of reachable values of the vectors of variables of the program, at this breakpoint. The simplest lattice expressing numerical invariants consists of Cartesian products of intervals. More sophisticated lattices, taking into account relations between variables, consisting in particular of subclasses of polyhedra, are often used.

As an illustration, we gave before Eqn (8) a simple example of program, together with the associated fixed-point equation. In this example, the value of the variable $x$ at the breakpoint 2 is bounded by the smallest solution $x_2^j$ of the fixed point problem (8), which is equal to 99.

The fixed point equation (8) is similar to the one arising in the theory of zero-sum repeated games. This analogy turns out to be general. Un a series of joint works of our team with the MeASI team of Eric Goubault (CEA and LIX), we brought progressively to light a correspondence [107], [123], between the zero-sum game problems and the static analysis problems, which can be summarized by the following dictionary:

<table>
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<td>exécution de n pas</td>
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</tr>
<tr>
<td>itération sur les valeurs</td>
<td>itération de Kleene</td>
</tr>
</tbody>
</table>
Games
dynamical system
Shapley operator
state space
horizon \( n \) problem
limit of the value in horizon \( n \)
value iteration

Abstract interpretation
program
functional
(# breakpoints) \( \times \) (# degrees of freedom)
execution of \( n \) logical steps
optimal invariant (bound)
Kleene iteration

For the game to have a finite state space, we must restrict our attention to lattices of sets with a finite number of degrees of freedom, which is the case of the domains commonly used in static analysis (intervals, sets defined by potentials constraints of the form \( x_i - x_j \leq \text{cst} \), and also the subclasses of polyhedra called “templates”, introduced recently by Sankaranarayanan, Sipma and Manna [175]). Then, the action space is finite if the arithmetics of the program is affine. However, in full generality, the games we end up with have a negative discount rate, which raises difficulties which are unfamiliar from the game theory point of view. This correspondence between games and static analysis turns out to be non intuitive, in that the action of the minimizer consist of selecting an extreme point of a polyhedron arising from a certain duality construction.

A well known pathology in static analysis is the fact that the standard Kleene fixed point algorithm may have a very slow behavior (99 iterations are needed to get the smallest fixed point of (8)). This is usually solved by using some accelerations of convergence, called widening and narrowing [109], which however lead to a loss of precision. We exploited the correspondence between static analysis and games to develop algorithms of a very different nature, inspired by our earlier work on policy iteration for games [124], [102], [103], [7]. A rather general version of this policy iteration algorithm, adapted to the domain of templates, is described in [123], together with a prototype implementation. Every iteration combines linear programming and combinatorial algorithms. Some experimental results indicate that the method often leads to invariants which are more accurate than the ones obtained by alternative methods, in particular for some programs with nested loops.

This topic of research is currently evolving, a question of current interest being to find accurate invariants, in a scalable way, in situations in which the arithmetics is not affine.

4.5. Autres applications/Other applications

L’algèbre max-plus apparaît de manière naturelle dans le calcul de scores de similitudes dans la comparaison de séquences génétiques. Voir par exemple [106].

English version

Max-plus algebra arises naturally in the computation of similarity scores, in biological sequence comparison. See for instance [106].
4. Application Domains

4.1. Application domains

Closing feedback loops around Wireless sensor networks offer new challenges and new opportunities for the area of control. Several new application areas can be enabled, or enhanced if systematic methods are developed for the design of NCS. Examples include:

- Intelligent buildings, where sensor information on CO$_2$ concentration, temperature, room occupancy, etc. can be used to control the heating, ventilation and air conditioning (HVAC) system under multi-objective considerations of comfort, air quality, and energy consumption.

- Intelligent transportation systems, where traffic flow or density can be measured using novel wireless technologies and used to determine control inputs such as on-ramp metering schemes and variable message signs.

- Disaster relief operations, where data collected by sensor networks can be used to guide the actions of rescue crews and operate automated rescue equipment.

- Surveillance using swarms of Uninhabited Aerial Vehicles (UAVs), where sensor information (from sensors on the ground and/or on-board the vehicles) can be used to guide the UAVs to accomplish their mission.

- Environmental monitoring and exploration using schools of Autonomous Underwater Vehicles (AUVs), where underwater sensors and communication are used to guide the AUVs.

- Infrastructure security and protection using smart camera networks, where the images collected are shared among the cameras and used to control the cameras themselves (pan-tilt-zoom) and ensure tracking of potential threat.

In particular, the team is already involved in the areas described in detail below.

4.1.1. Vehicular transportation systems

4.1.1.1. Car industry

Car industry has been already identified as a potential homeland application for NCS [76], as the evolution of micro-electronics paved the way for introducing distributed control in vehicles. In addition, automotive control systems are becoming more complex and iterative, as more on-board sensors and actuators are made available through technology innovations. The increasing number of subsystems, coupled with overwhelming information made available through on-board and off-board sensors and communication systems, rises new and interesting challenges to achieve optimal performance while maintaining the safety and the robustness of the total system. Causes of such an increase of complexity/difficulties are diverse: interaction between several control sub-systems (ABS, TCS, ESP, etc.), loose of synchrony between sub-systems, limitations in the computation capabilities of each dedicated processor, etc. The team had several past collaborations with the car industry (Renault since 1992, and Ford). In addition, an ANR project, named VOLHAND, has been started in collaboration with INRETS, JTEKT, Fondation Hopale, LAMIH, CHRU. It aims at developing a new generation of electrical power-assisted steering specifically designed for disabled and aged persons.
4.1.1.2. Intelligent transportation systems

Throughout the world, roadways are notorious for their congestion, from dense urban network to large freeway systems. This situation tends to get worse over time due to the continuous increase of transportation demand whereas public investments are decreasing and space is lacking to build new infrastructures. The most obvious impact of traffic congestion for citizens is the increase of travel times and fuel consumption. Another critical effect is that infrastructures are not operated at their capacity during congestion, implying that fewer vehicles are served than the amount they were designed for. Using macroscopic fluid-like models, the NeCS team has initiated new researches to develop innovative traffic management policies able to improve the infrastructure operations. This activity is currently focused on automatic model calibration and traffic prediction, two important items to implement efficient Intelligent Transportation Systems (ITS) such as traffic responsive ramp metering and varying speed limit as well as producing relevant user information. The team is currently setting up a consortium with local authorities involved in traffic management to build to a demonstrator called GTL (Grenoble Traffic Lab). One target of this activity is to transfer part of the developed technology to a start-up named Karrus.

4.1.2. Underwater systems

Underwater systems, as presently used or intended by the offshore industry and marine research, are subject to severe technological constraints. In AUVs, the on-board power is limited and calls for both control and computing optimization. The links between the master and slave nodes use acoustic devices, which have a very low bandwidth and are subject to frequent transient loss, thus calling for sharing the decisional process among the nodes and for a robust implementation of the distributed control, taking into account the communication network features. These constraints together with the potential cost of failures make these systems good candidates for safe and flexible control, communication and computing co-design. The team already got a significant experience in this domain with a past collaboration with IFREMER and other EU projects. The projects CONNECT and FeedNetBack are dealing with this type of problems (see Sections 8.2 and 8.3).

4.1.3. Systems on chip

Achieving a good compromise between computing power and energy consumption is one of the challenge in embedded architecture of the future. This management is especially difficult for 45nm or 32nm known to be at the limit of the scalability. Automatic control loops have therefore to be designed in order to make the performance fit the requirement in order to minimize the energy loss in a context of highly unknown performance of the chip. The main objective is to control the computing power and the consumption using the voltage and frequency automatically according to the requirements of the OS. For this, appropriate sensors must be implemented on the chip and a high-performance repartition between hardware and software implementation must be made.
4. Application Domains

4.1. Application domains

Unlike the traditional methods, the estimators we defined are “non-asymptotic”: solutions are provided by explicit formulae. They result in relatively simple and fast algorithms. In this sense, rather than being a project linked to a specific domain of application, we can say that the present project Non-A is a method-driven project. However, one must not forget that applicability remains a guideline in all our research. As it was told, estimation is a huge area, which explains the variety of possible application fields our new methods address. Figure 3 illustrates the connections between our techniques and the possible applications.

During these first few years, our techniques have already generated 3 patents [77], [79], [78]. It shows their efficiency in various industrial domains, including (see the previous reports):

- Vehicle control (engine throttle [94], lateral and longitudinal velocities [73], stop-and-go [114], tire/road contact condition [118]) with PSA, APEDGE, Mines-ParisTech, INRIA IMARA, Universidad Carlos III (Madrid), Université Paris Sud;
- Hydroelectric power plants [93], [92] with EDF-CIH (patent pending FR0858532);
- Shape memory actuators [89] with Université de Bretagne Occidentale and ANR MAFESMA;
• Magnetic actuators with Univ. des Saarlandes;
• Power Electronics [103] with Univ. du Québec à Trois-Rivières;
• Aircraft identification [113] with ONERA DCSD;
• Secured communications (chaos-based cryptography [111], [120], [119], CPM demodulation [104]) with CINVESTAV Mexico, Math.Dept. Tlemcen Univ. Algeria and PRISME ENSI-Bourges.
• Image and video processing (denoising [83], edge detection [95]) with INRIA QGAR, compression [84], compressive sensing [116], [117] with CINVESTAV Mexico and Whuan Univ., China.
• More recently, financial engineering [76] with MEREOR Investment Management and Advisory SAS.
4. Application Domains

4.1. Forecasting of the electricity consumption

Our partner is EDF R&D. The goal is to aggregate in a sequential fashion the forecasts made by some (about 20) base experts in order to predict the electricity consumption at a global level (the one of all French customers) at a half-hourly step. We need to abide by some operational constraints: the predictions need to be made at noon for the next 24 hours (i.e., for the next 48 time rounds).

4.2. Forecasting of the air quality

Our partner is the INRIA project-team CLIME (Paris-Rocquencourt). The goal is to aggregate in a sequential fashion the forecasts made by some (about 100) base experts in order to output field prediction of the concentration of some pollutants (typically, the ozone) over Europe. The results were and will be transferred to the public operator INERIS, which uses and will use them in an operational way.

4.3. Management of the supply chain

Our partner is the start-up Lokad.com. The purpose of this application is to investigate nonparametric expert-oriented strategies for time series prediction from a practical perspective.

4.4. Computational linguistics

The aim is to propose and study new language models that bridge the gap between models oriented towards statistical analysis of large corpora and grammars oriented towards the description of syntactic features as understood by academic experts.

4.5. Statistical inference on biological data

We have here two specific applications in mind.

One is about understanding how the transcription of human genome is performed: transcription regulatory elements need to be identified. A natural modeling is provided by multivariate Hawkes processes but an excessive computational time is necessary for their implementation. Lasso type methods may overcome this numerical issue.

The second is about estimating the division rate of a size-structured population in a nonparametric setting. The size of the system evolves according to a transport-fragmentation equation: each individual grows with a given transport rate and splits into two offsprings of the same size, following a binary fragmentation process with an unknown division rate that depends on its size.
4. Application Domains

4.1. Academic generic problems

In this project, some well known optimization problems are re-visited in terms of multi-objective modelization and resolution:

- **Workshop optimization problems:**
  Workshop optimization problems deal with optimizing the production. In this project, two specific problems are under study.
  - **Flow-shop scheduling problem:** The flow-shop problem is one of the most well-known scheduling problems. However, most of the works in the literature use a mono-objective model. In general, the minimized objective is the total completion time (makespan). Many other criteria may be used to schedule tasks on different machines: maximum tardiness, total tardiness, mean job flowtime, number of delayed jobs, maximum job flowtime, etc. In the DOLPHIN project, a bi-criteria model, which consists in minimizing the makespan and the total tardiness, is studied. A tri-criteria flow-shop problem, minimizing in addition the maximum tardiness, is also studied. It allows us to develop and test multi-objective (and not only bi-objective) exact methods.
  - **Cutting problems:** Cutting problems occur when pieces of wire, steel, wood, or paper have to be cut from larger pieces. The objective is to minimize the quantity of lost material. Most of these problems derive from the classical one-dimensional cutting-stock problem, which have been studied by many researchers. The problem studied by the DOLPHIN project is a two-dimensional bi-objective problem, where rotating a rectangular piece has an impact on the visual quality of the cutting pattern. First we have to study the structure of the cutting-stock problem when rotation is allowed, then we will develop a method dedicated to the bi-objective version of the problem.

- **Logistics and transportation problems:**
  - **Packing problems:** In logistic and transportation fields, packing problems may be a major issue in the delivery process. They arise when one wants to minimize the size of a warehouse or a cargo, the number of boxes, or the number of vehicles used to deliver a batch of items. These problems have been the subjects of many papers, but only few of them study multi-objective cases, and to our knowledge, never from an exact point of view. Such a case occurs for example when some pairs of items cannot be packed in the same bin. The DOLPHIN project is currently studying the problem in its one-dimensional version. We plan to generalize our approach to two and three dimensional problems, and to more other conflict constraints, with the notion of distance between items.
  - **Routing problems:** The vehicle routing problem (VRP) is a well-known problem and it has been studied since the end of the 50’s. It has a lot of practical applications in many industrial areas (ex. transportation, logistics, etc). Existing studies of the VRP are almost all concerned with the minimization of the total distance only. The model studied in the DOLPHIN project introduces a second objective, whose purpose is to balance the length of the tours. This new criterion is expressed as the minimization of the difference between the length of the longest tour and the length of the shortest tour. As far as we know, this model is one of the pioneer work in the literature.
The second routing problem is a generalization of the covering tour problem (CTP). In the DOLPHIN project, this problem is solved as a bi-objective problem where a set of constraints are modeled as an objective. The two objectives are: i) minimization of the length of the tour; ii) minimization of the largest distance between a node to be covered and a visited node. As far as we know, this study is among the first works that tackle a classic mono-objective routing problem by relaxing constraints and building a more general MOP.

The third studied routing problem is the Ring Star Problem (RSP). This problem consists in locating a simple cycle through a subset of nodes of a graph while optimizing two kinds of costs. The first objective is to minimize a ring cost that is related to the length of the cycle. The second one is to minimize an assignment cost from non-visited nodes to visited ones. In spite of its natural bi-criteria formulation, this problem has always been studied in a single-objective form where either both objectives are combined or one objective is treated as a constraint.

Recently, within a cooperation with SOGEP, the logistic and delivery subsidiary company of REDCATS (PINAULT PRINTEMPS REDOUTE), a new routing problem is under study. Indeed, the COLIV AD project consists in solving a logistic and transportation problem that has been reduced to a vehicle routing problem with additional constraints. First we are designing a method to solve exactly a bi-objective version of the problem in order to evaluate the interest of modifying the current process of delivery. We are also working on the resolution of a single-objective version of this problem to design an operational tool dedicated to the SOGEP problem.

For all studied problems, standard benchmarks have been extended to the multi-objective case. The benchmarks and the obtained results (optimal Pareto front, best known Pareto front) are available on the Web pages associated to the project and from the MCDM (International Society on Multiple Criteria Decision Making) Web site. This is an important issue to encourage comparison experiments in the research community.

4.2. Application to mobile telecommunication networks

With the extraordinary success of mobile telecommunication systems, service providers have been affording huge investments for network design and infrastructure. Mobile network design is of outmost importance, and is thus a major issue in mobile telecommunication systems. In fact, with the continuous and rapid growth of communication traffic, large scale planning becomes more and more difficult. Hence, automatic, interactive and self-adaptive optimization algorithms and tools would be very useful and helpful. Advances in this area will certainly lead to important improvements in terms of quality of service, network management and cost deployment.

In the past, the DOLPHIN team has initiated solid industrial collaborations within the domain of mobile networks. In fact, the problem of network design and frequency assignment was studied in collaboration with France Telecom. In particular, a new formulation/resolution of the problem as a multi-objective constrained combinatorial optimization problem was considered. In collaboration with Mobinets, the DOLPHIN team has also addressed the problem of access network design. The problem consists in minimizing the cost of the access network and maximizing its availability.

More recently, the DOLPHIN team has been interested in new optimization models and algorithms to address new difficult problems raised by new emerging technologies in wireless networks. In fact, wireless communications are evolving from inflexible and monolithic systems to a composite radio environment made of cognitive radio devices and networks of different technologies. Within this context, the challenge is to design new optimization techniques which are not only resource, power, scale, and applications aware, but which are self-adaptive and fully distributed in order to allow the dynamic optimization of radio-devices behaviors depending on the environment constraints e.g., spectrum availability, network traffic, user demand, etc. To achieve this goal, distributed and nature-inspired algorithms, such as ant-colony and bees, will be investigated in order to dynamically and distributively optimize predefined criterion such as throughput, fairness, quality
of service to cite a few. It is expected that the techniques developed in this work will lead to the design of new models and algorithms for opportunistic/dynamic spectrum access and cross layer network optimization which are at the core of future generation wireless networks.

4.3. Application to Bioinformatics

Bioinformatic research is a great challenge for our society and numerous research entities of different specialities (biology, medical or information technology) are collaborating on specific thema.

4.3.1. Genomic and post-genomic studies

Previous studies of the DOLPHIN project mainly deal with genomic and postgenomic applications. These have been realized in collaboration with academic and industrial partners (IBL: Biology Institute of Lille; IPL: Pasteur Institute of Lille; IT-Omics firm).

First, genomic studies aim to analyze genetic factors which may explain multi-factorial diseases such as diabetes, obesity or cardiovascular diseases. The scientific goal was to formulate hypotheses describing associations that may have any influence on diseases under study.

Secondly, in the context of post-genomic, a very large amount of data are obtained thanks to advanced technologies and have to be analyzed. Hence, one of the goals of the project was to develop analysis methods in order to discover knowledge in data coming from biological experiments.

These problems can be modeled as classical datamining tasks (Association rules, feature selection). As the combinatoric of such problems is very high and the quality criteria not unique, we proposed to model these problems as multi-objective combinatorial optimization problems. Evolutionary approaches have been adopted in order to cope with large scale problems.

Nowadays the technology is still going fast and the number of data increases rapidly. Within the new collaboration, started in 2010, with Genes Diffusion, specializes in genetics and animal reproduction for bovine, swine, equine and rabbit species, we will study combinations of Single Nucleotide Polymorphisms (SNP) that can explain some phenotypic characteristics.

4.3.2. Docking and conformational sampling

In molecular modelling, conformational sampling and docking procedures provide help for understanding the interaction mechanisms between (macro)molecules involved in physiological processes. The processes to be simulated are of a combinatorial complexity (molecule size, number of degrees of freedom) which represents an important challenge for the currently available computing power. Such a challenge can be expressed by three major objectives: (1) the proposition of mathematical models of maximum simplicity that nevertheless provide a relevant description of molecular behavior, (2) the development of powerful distributed optimization algorithms (evolutionary algorithms, local search methods, hybrid algorithms) for sampling the molecular energy surface for stable, populated conformations, and (3) the deployment of those intrinsic distributed algorithms on computational Grids.

Within the framework of ANR DOCK and Decrypton projects, the focus was to propose multi-objective formulations of the conformational and docking problems. The goal was to take into account different criteria characteristics of the complex docking process. Furthermore, in order to deal with the multimodal nature of the problems it is important to define new hybrid mechanisms allowing us to provide algorithms with both diversification and intensification properties. Finally, to deal with the exponential combinatorial of these problems when large proteins are concerned parallel and grid computing is highly required. Using grid computing is not straightforward, so a "gridification" process is necessary. Such process allows us to adapt the proposed algorithms to the characteristics of the grid. The gridification process must be exploited by the user in a transparent way. Therefore, coupling ParadisEO-PEO with a generic grid middleware such as Globus is important to provide robust and efficient algorithms to be exploited transparently.

New contacts with the Servier company show that these questions are really challenging ones for the design of new drug molecules.
4.3.3. Optimization for health care

The new collaboration (PhD thesis started in October 2010) with Alicante company, major actor in the hospital decision making, will deal with knowledge extraction by optimization methods for improving the process of inclusion in clinical trials. Indeed, conducting a clinical trial, allowing for example to measure the effectiveness of a treatment, involves selecting a set of patients likely to participate to this test. Currently existing selection processes are far from optimal, and many potential patients are not considered. The objective of this collaboration consists in helping the practitioner to quickly determine if a patient is interesting for a clinical trial or not. Exploring different data sources (from a hospital information system, patient data...), a set of decision rules have to be generated. For this, approaches from combinatorial optimization will be implemented, requiring extensive work to model the problem, to define criteria optimization and to design specific optimization methods.
4. Application Domains

4.1. Application Domains

The following application domains are investigated by the GEOSTAT team:

- Complex signal acquired from remote sensing and earth observation, notably in Oceanography, and ocean/climate interaction.
- Speech signal.
- Astronomical imaging and turbulence (in collaboration with LATT and ONERA).
- Analysis of heartbeat signals (in collaboration with M. Haissaguerre, head of team INSERM EA3668 Electrophysiologie et Stimulation Cardiaque, Bordeaux University, R. Dubois (ESPCI) and the CARMEN team).
MISTIS Project-Team (section vide)
4. Application Domains

4.1. Application Domains

Potential application areas of statistical modeling for heterogeneous data are extensive but some particular areas are identified. For historical reasons and considering the background of the team members, MODAL is mainly focused on biological applications where new challenges in high throughput technologies are opened. In addition, other secondary application areas are considered as industry, retail, credit scoring and astronomy. Several contacts and collaborations are already established with some partners in these application areas and are described in Sections 7 and 8.
4. Application Domains

4.1. Introduction

Our group has tackled applications in logistics, transportation and routing [67], [66], [63], [65], in production planning [44], [84] and inventory control [63], [65], in network design and traffic routing [46], [54], [64], [89], [42], [55], [60], [72], [79], in cutting and placement problems [70], [71], [81], [82], [83], [85], and in scheduling [8], [74].

4.2. Network Design and Routing Problems

We are actively working on problems arising in network topology design, implementing a survivability condition of the form “at least two paths link each pair of terminals”. We have extended polyhedral approaches to problem variants with bounded length requirements and re-routing restrictions [54]. Associated to network design is the question of traffic routing in the network: one needs to check that the network capacity suffices to carry the demand for traffic. The assignment of traffic also implies the installation of specific hardware at transient or terminal nodes.

To accommodate the increase of traffic in telecommunication networks, today’s optical networks use grooming and wavelength division multiplexing technologies. Packing multiple requests together in the same optical stream requires to convert the signal in the electrical domain at each aggregation of disaggregation of traffic at an origin, a destination or a bifurcation node. Traffic grooming and routing decisions along with wavelength assignments must be optimized to reduce opto-electronic system installation cost. We developed and compared several decomposition approaches [91], [90], [89] to deal with backbone optical network with relatively few nodes (around 20) but thousands of requests for which traditional multi-commodity network flow approaches are completely overwhelmed. We also studied the impact of imposing a restriction on the number of optical hops in any request route [88]. We also developed a branch-and-cut approach to a problem that consists in placing sensors on the links of a network for a minimum cost [61], [62].

We studied several time dependent formulations for the unit demand vehicle routing problem [48], [47]. We gave new bounding flow inequalities for a single commodity flow formulation of the problem. We described their impact by projecting them on some other sets of variables, such as variables issued of the Picard and Queyranne formulation or the natural set of design variables. Some inequalities obtained by projection are facet defining for the polytope associated with the problem. We are now running more numerical experiments in order to validate in practice the efficiency of our theoretical results.

We also worked on the p-median problem, applying the matching theory to develop an efficient algorithm in Y-free graphs and to provide a simple polyhedral characterization of the problem and therefore a simple linear formulation [78] simplifying results from Baiou and Barahona.

4.3. Packing and Covering Problems

We developed a branch-and-price algorithm for the Bin Packing Problem with Conflicts which improves on other approaches available in the literature [21]. The algorithm uses our methodological advances like the generic branching rule for the branch-and-price and the column based heuristic. One of the ingredients which contributes to the success of our method are fast algorithms we developed for solving the subproblem which is the Knapsack Problem with Conflicts. Two variants of the subproblem have been considered: with interval and arbitrary conflict graphs. The paper which presents this work is being finalized.

We have designed a new algorithm for vertex packing (equivalently stable set) in claw-free graphs [68]. Previously the best known algorithm for this problem had a running time of $O(n^6)$ (with $n$ the number of vertices in the graph) while our new algorithm runs in $O(n^4)$. 
We studied a variant of the knapsack problem encountered in inventory routing problem \cite{65}: we faced a multiple-class integer knapsack problem with setups \cite{64} (items are partitioned into classes whose use implies a setup cost and associated capacity consumption). We showed the extent to which classical results for the knapsack problem can be generalized to this variant with setups and we developed a specialized branch-and-bound algorithm.

We studied the orthogonal knapsack problem, with the help of graph theory \cite{59}, \cite{57}, \cite{14}, \cite{13}. Fekete and Schepers proposed to model multi-dimensional orthogonal placement problems by using an efficient representation of all geometrically symmetric solutions by a so called packing class involving one interval graph for each dimension. Though Fekete & Schepers’ framework is very efficient, we have however identified several weaknesses in their algorithms: the most obvious one is that they do not take advantage of the different possibilities to represent interval graphs. We propose to represent these graphs by matrices with consecutive ones on each row. We proposed a branch-and-bound algorithm for the 2d knapsack problem that uses our 2D packing feasibility check.

### 4.4. Planning, Scheduling, and Logistic Problems

Inventory routing problems combine the optimization of product deliveries (or pickups) with inventory control at customer sites. We considered an industrial application where one must construct the planning of single product pickups over time; each site accumulates stock at a deterministic rate; the stock is emptied on each visit. We have developed a truncated branch-and-price algorithm: periodic plans are generated for vehicles by solving a multiple choice knapsack subproblem; the global planning of customer visits is generated by solving a master program. Confronted with the issue of symmetry in time, we used a state-space relaxation idea. Our algorithm provides solutions with reasonable deviation from optimality for large scale problems (260 customer sites, 60 time periods, 10 vehicles) coming from industry \cite{15}. We previously developed approximate solutions to a related problem combining vehicle routing and planning over a fixed time horizon (solving instances involving up to 6000 pick-ups and deliveries to plan over a twenty day time horizon with specific requirements on the frequency of visits to customers \cite{67}. 

![Design of a SDH/SONET european network where demands are multiplexed.](image)
We participated to the project on an airborne radar scheduling. For this problem, we developed fast heuristics [53] and exact algorithms [39]. A substantial research has been done on machine scheduling problems. A new compact MIP formulation was proposed for a large class of these problems [38]. An exact decomposition algorithm was developed for the NP-hard maximizing the weighted number of late jobs problem on a single machine [74]. A dominant class of schedules for malleable parallel jobs was discovered in the NP-hard problem to minimize the total weighted completion time [76]. We proved that a special case of the scheduling problem at cross docking terminals to minimize the storage cost is polynomially solvable [77], [75]. Finally, we participated in writing an invited survey in French on solution approaches for machine scheduling problems in general [40].

Another application area in which we have successfully developed MIP approaches is in the area of tactical production and supply chain planning. In [37], we proposed a simple heuristic for challenging multi-echelon problems that makes effective use of a standard MIP solver. [36] contains a detailed investigation of what makes solving the MIP formulations of such problems challenging; it provides a survey of the known methods for strengthening formulations for these applications, and it also pinpoints the specific substructure that seems to cause the bottleneck in solving these models. Finally, the results of [41] provide demonstrably stronger formulations for some problem classes than any previously proposed.

We have been developing robust optimization models and methods to deal with a number of applications like the above in which uncertainty is involved. In [50], [49], we analyzed fundamental MIP models that incorporate uncertainty and we have exploited the structure of the stochastic formulation of the problems in order to derive algorithms and strong formulations for these and related problems. These results appear to be the first of their kind for structured stochastic MIP models. In addition, we have engaged in successful research to apply concepts such as these to health care logistics [43]. We considered train timetabling problems and their re-optimization after a perturbation in the network [52], [51]. The question of formulation is central. Models of the literature are not satisfactory: continuous time formulations have poor quality due to the presence of discrete decision (re-sequencing or re-routing); arc flow in time-space graph blow-up in size (they can only handle a single line timetabling problem). We have developed a discrete time formulation that strikes a compromise between these two previous models. Based on various time and network aggregation strategies, we develop a 2-stage approach, solving the contiguous time model having fixed the precedence based on a solution to the discrete time model.
4. Application Domains

4.1. Introduction

A key goal of SELECT is to produce methodological contributions in statistics. For this reason, the SELECT team works with applications that serve as an important source of interesting practical problems and require innovative methodologies to address them. Most of our applications involve contracts with industrial partners, e.g. in reliability, although we also have several more academic collaborations, e.g. genomics, genetics and neuroimaging.

4.2. Curves classification

The field of classification for complex data as curves, functions, spectra and time series is important. Standard data analysis questions are being revisited to define new strategies that take the functional nature of the data into account. Functional data analysis addresses a variety of applied problems, including longitudinal studies, analysis of fMRI data and spectral calibration.

We are focusing on unsupervised classification. In addition to standard questions as the choice of the number of clusters, the norm for measuring the distance between two observations, and the vectors for representing clusters, we must also address a major computational problem. The functional nature of the data needs to be design efficient anytime algorithms.

4.3. Computer Experiments and Reliability

Since several years, SELECT has collaborations with EDF-DER Maintenance des Risques Industriels group. An important theme concerns the resolution of inverse problems using simulation tools to analyze incertainty in highly complex physical systems. A collaboration on an analogous topic is developed with Dassault Aviation.

The other major theme concerns probabilistic modeling in fatigue analysis in the context of a research collaboration with SAFRAN an high-technology group (Aerospace propulsion, Aircraft equipment, Defense Security, Communications).

4.4. Neuroimaging

Since 2007 SELECT participates to a working group with team Neurospin (CEA-INSERM-INRIA) on Classification, Statistics and fMRI (functional Magnetic Resonance Imaging) analysis. In this framework two theses have been co-supervised by SELECT and Neurospin researchers (Merlin Keller 2006-2009 and Vincent Michel 2007-2010). The aim of this research is to determine which parts of the brain are activated by different types of stimuli. A model selection approach is useful to avoid "false-positive" detections.

4.5. Analysis of genomic data

For the past few years SELECT has collaborated with Marie-Laure Martin-Magniette (URGV) for the analysis of genomic data. An important theme of this collaboration is using statistically sound model-based clustering methods to discover groups of co-expressed genes from microarray and high-throughput sequencing data. In particular, identifying biological entities that share similar profiles across several treatment conditions, such as co-expressed genes, may help identify groups of genes that are involved in the same biological processes.
4.6. Environment

A study has been achieved by Jean-Michel Poggi, François-Xavier Jollois (Université Paris-Descartes) and Bruno Portier (INSA de Rouen), in the context of a collaboration between AirNormand, Paris Descartes University and INSA of Rouen. They analyzed and forecasted PM10 pollution in Rouen area on six different monitoring sites to quantify the effects of variables of different types, mainly meteorological versus other pollutant measurements. Some recent non parametric statistical methods (random forests, mixture of linear models and nonlinear additive models) have been used and beyond the application, this study shed light on those methods.
4. Application Domains

4.1. Outline

SEQUEL aims at solving problems of prediction, as well as problems of optimal and adaptive control. As such, the application domains are very numerous.

The application domains have been organized as follows:

- adaptive control,
- signal analysis and processing,
- functional prediction,
- neuroscience.

4.2. Adaptive control

Adaptive control is an important application of the research being done in SEQUEL. Reinforcement learning (RL) precisely aims at controlling the behavior of systems and may be used in situations with more or less information available. Of course, the more information, the better, in which case methods of (approximate) dynamic programming may be used [77]. But, reinforcement learning may also handle situations where the dynamics of the system is unknown, situations where the system is partially observable, and non stationary situations. Indeed, in these cases, the behavior is learned by interacting with the environment and thus naturally adapts to the changes of the environment. Furthermore, the adaptive system may also take advantage of expert knowledge when available.

Clearly, the spectrum of potential applications is very wide: as far as an agent (a human, a robot, a virtual agent) has to take a decision, in particular in cases where he lacks some information to take the decision, this enters the scope of our activities. To exemplify the potential applications, let us cite:

- game softwares: in the 1990’s, RL has been the basis of a very successful Backgammon program, TD-Gammon [83] that learned to play at an expert level by basically playing a very large amount of games against itself. Today, various games are studied with RL techniques.
- many optimization problems that are closely related to operation research, but taking into account the uncertainty, and the stochasticity of the environment: see the job-shop scheduling, or the cellular phone frequency allocation problems, resource allocation in general [77]
- we can also foresee that some progress may be made by using RL to design adaptive conversational agents, or system-level as well as application-level operating systems that adapt to their users habits.

More generally, these ideas fall into what adaptive control may bring to human beings, in making their life simpler, by being embedded in an environment that is made to help them, an idea phrased as “ambient intelligence”.

- The sensor management problem consists in determining the best way to task several sensors when each sensor has many modes and search patterns. In the detection/tracking applications, the tasks assigned to a sensor management system are for instance:
  - detect targets,
  - track the targets in the case of a moving target and/or a smart target (a smart target can change its behavior when it detects that it is under analysis),
  - combine all the detections in order to track each moving target,
  - dynamically allocate the sensors in order to achieve the previous three tasks in an optimal way. The allocation of sensors, and their modes, thus defines the action space of the underlying Markov decision problem.
In the more general situation, some sensors may be localized at the same place while others are dispatched over a given volume. Tasking a sensor may include, at each moment, such choices as where to point and/or what mode to use. Tasking a group of sensors includes the tasking of each individual sensor but also the choice of collaborating sensors subgroups. Of course, the sensor management problem is related to an objective. In general, sensors must balance complex trade-offs between achieving mission goals such as detecting new targets, tracking existing targets, and identifying existing targets. The word “target” is used here in its most general meaning, and the potential applications are not restricted to military applications. Whatever the underlying application, the sensor management problem consists in choosing at each time an action within the set of available actions.

- sequential decision processes are also very well-known in economy. They may be used as a decision aid tool, to help in the design of social helps, or the implementation of plants (see [81], [80] for such applications).

4.3. Signal analysis and processing

Applications of sequential learning in the field of signal processing are also very numerous. A signal is naturally sequential as it flows. It usually comes from the recording of the output of sensors but the recording of any sequence of numbers may be considered as a signal like the stock-exchange rates evolution with respect to time and/or place, the number of consumers at a mall entrance or the number of connections to a web site. Signal processing has several objectives: predict, estimate, remove noise, characterize or classify. The signal is often considered as sequential: we want to predict, estimate or classify a value (or a feature) at time $t$ knowing the past values of the parameter of interest or past values of data related to this parameter.

Signals may be processed in several ways. One of the best way is the time-frequency analysis in which the frequencies of each signal are analyzed with respect to time. This concept has been generalized to the time-scale analysis obtained by a wavelet transform. Both analysis are based on the projection of the original signal onto a well-chosen function basis. Signal processing is also closely related to the probability field as the uncertainty inherent to many signals leads to consider them as stochastic processes: the Bayesian framework is actually one of the main frameworks within which signals are processed for many purposes. However, there exists alternatives like belief functions. Belief functions were introduced by Dempster few decades ago and have been successfully used in the past few years in fields where probability had, during many years, no alternatives like in classification. Belief functions can be viewed as a generalization of probabilities which can capture both imprecision and uncertainty. Belief functions are also closely related to data fusion where once more they can be considered as a serious alternative to probabilities.

4.4. Functional prediction

One of the current trends in machine learning aims at dealing with data that are functions, rather than points or vectors. Generally speaking, functions represent a behavior (of a person, of an apparatus, or of an algorithm, or a response of a system, ...).

One application of functional prediction which is particularly emphasized these days, is the understanding of client behavior, either in material shops, or in virtual shops on the web. This understanding may then be used for different ends, such as the management of stocks according to sales, the proposition of products according to those already bought, the “instantaneous” management of some resource in the shop (advisors, cashiers, instant promotions, personalized advertisement, ...).

4.5. Neuroscience

Machine learning methods may be used for at least two means in neurosciences:

1. as in any other (experimental) scientific domain, the machine learning methods relying heavily on statistics, they may be used to analyse experimental data,
2. dealing with induction learning, that is the ability to generalize from facts which is an ability that is considered to be one of the basic components of “intelligence”, machine learning may be considered as a model of learning in living beings. In particular, the temporal difference methods for reinforcement learning has strong ties with various concepts of psychology (Thorndike’s law of effect, and the Rescorla-Wagner law to name the two most well-known).
4. Application Domains

4.1. Application Domains

Machine learning research can be conducted from two main perspectives: the first one, which has been dominant in the last 30 years, is to design learning algorithms and theories which are as generic as possible, the goal being to make as few assumptions as possible regarding the problems to be solved and to let data speak for themselves. This has led to many interesting methodological developments and successful applications. However, we believe that this strategy has reached its limit for many application domains, such as computer vision, bioinformatics, neuro-imaging, text and audio processing, which leads to the second perspective our team is built on: Research in machine learning theory and algorithms should be driven by interdisciplinary collaborations, so that specific prior knowledge may be properly introduced into the learning process, in particular with the following fields:

- Computer vision: objet recognition, object detection, image segmentation, image/video processing, computational photography.
- Bioinformatics: cancer diagnosis, protein function prediction, virtual screening.
- Text processing: document collection modeling, language models.
- Audio processing: source separation, speech/music processing.
- Neuro-imaging: brain-computer interface (fMRI, EEG, MEG).
4. Application Domains

4.1. Application Domains

Since its creation, TAO mainstream applications regard Numerical Engineering, Autonomous Robotics, and Control and Games. Two new fields of applications, due to the arrival of Cécile Germain (Pr UPS, 2005), Philippe Caillou (MdC, 2005), Balázs Kégl (CR CNRS LAL, 2006) and Cyril Furtlehner (CR INRIA, 2007) have been considered: Autonomic Computing and Complex Systems.

**Numerical Engineering** still is a major source of applications. The successful OMD (Optimization Multi-Disciplinaire) RNTL/ANR project is being resumed by OMD2, started in July 2009. Collaborations with IFP and PSA automobile industry respectively led to Zyed Bouzarkouna’s and Mouadh Yagoubi’s PhD CIFRE. TAO leads the Work Package “Optimization” in the System@tic CSDL project, responsible for both fundamental research on surrogate models in multi-objective optimization and the setup of a software platform, that lead to Ilya Loshchilov’s PhD work. A collaboration with CEA DM2S was conducted as a Digiteo project and lead to Philippe Rolet’s PhD on simplified models.

**Autonomous Software Robotics** is rooted in our participation to the SYMBRION European IP and SyDiN-MaLaS (ANR-JST, coll. University of Kyushu). On this topic, Jean-Marc Montanier started his PhD in Sept. 2009; Vladimir Skortsov did his Post-doc from Sept. 2009 to Sept. 2010; Weijia Wang and Riad Akrour started their PhDs in Sept. 2010. See Section 6.2.

Our activity in **Control and Games** is chiefly visible through Mogo, already mentioned in the Highlights. Another application regards Brain Computer Interfaces: the Digiteo project Digibrain (coll. with CEA List and Neurospin), with Cedric Gouy-Pailler’s postdoc from October 2009 to October 2010.

Applications related to **Autonomic Computing** became an important part of TAO activities, led by Cécile Germain and Balázs Kégl in tight collaboration with the Laboratoire de l’Accélérateur Linéaire (section 6.1). Applications related to **Social Systems** are led by Philippe Caillou and Cyril Furtlehner, respectively investigating multi-agent models for labor market, and road traffic models (ANR project TRAVESTI, coordinated by C. Furtlehner, started in 2009). Last but not least, the arrival in TAO of Jamal Atif brought a new application field in image analysis and understanding.
4. Application Domains

4.1. Application Domains

This short section is only concerned with the list of concrete application domains developed by our team project on Bayesian inference and unsupervised learning, nonlinear filtering and rare event analysis. Most of these application areas result from fruitful collaborations with other national institutes through a series of four recently selected ANR research projects and one INRIA-INRA joint research project.

Three application domains are directly related to evolutionary computing, particle filtering and Bayesian inference. They are currently investigated by our team project:

1. Multi-target tracking: Multi-target tracking deals with the task of estimating the states of a set of moving targets from a set of measurements obtained sequentially. These measurements may either arise from one of the targets or from clutter and the measurement-to-target association is generally unknown. This problem can then be recast as a dynamic clustering one where the clusters are the clutter and the different targets. The targets actually move in time, some targets may appear/disappear over time and the number of targets is generally unknown and time-varying. We are running this research project with the DCNS-SIS division in Toulon.

2. Forecasting and Data assimilation: This new application domain concerns the application of the particle filter technology and more general sequential Monte Carlo methods to data assimilation problems arising in forecasting. The ALEA team project is involved in the ANR 2008 selected project PREVASSEMBLE with Météo France Toulouse, the INRIA Rennes and the LMD in Paris.

3. Virtual prairie: This application domain of evolutionary computing is concerned with the design of ecological systems, mixed-species models and prairial ecosystems. For more details, we refer the reader to the web site of the Virtual Prairie project. The ALEA project is a partner of the 2008 ANR SYSCOM project named MODECOL.

Three other application domains are directly related to rare event analysis using particle stochastic simulations techniques. These projects are currently investigated by our team project, two of them are 2008’s ANR research projects:

1. Watermarking of digital contents: The terminology watermarking refers to a set of techniques for imbedding/hiding information in a digital audio or video file, such that the change is not noticed, and very hard to remove. In order to be used in an application, a watermarking technique must be reliable. Protection false alarms and failures of traceability codes are practically not achievable without using rare event analysis. This application domain area of particle rare event technology is the subject of joint ANR 2007 research project with the IRISA-INRIA in Rennes and the LIS INPG in Grenoble.

2. Epidemic propagations analysis: This project aims at developing stochastic mathematical models for the spread of transmissible infectious diseases, together with dedicated statistical methodologies, with the intent to deliver efficient diagnostic/prediction tools for epidemiologists. This application domain area of particle rare event technology is the subject of joint ANR 2008 research project with Telecom ParisTech, the Laboratoire Paul Painlevé in Lille 1 and the University of Paris 5 (cf. Programme Systèmes Complexes et Modélisation Mathématique, list of 2008 selected projects).

3. Statistical eco-microbiology predictions:
This project aims at developing stochastic models and algorithms for the analysis of bacteriology ecosystems, especially in food safety. The objective is to predict and control critical risk of proliferations. This is the subject of joint research project with the INRA of Paris and Montpellier (Appel d’Offre INRIA-INRA 2008 : Systèmes Complexes).
4. Application Domains

4.1. Localisation, navigation and tracking

Among the many application domains of particle methods, or interacting Monte Carlo methods, ASPI has decided to focus on applications in localisation (or positioning), navigation and tracking, which already covers a very broad spectrum of application domains. The objective here is to estimate the position (and also velocity, attitude, etc.) of a mobile object, from the combination of different sources of information, including:

- a prior dynamical model of typical evolutions of the mobile, such as inertial estimates and prior model for inertial errors,
- measurements provided by sensors,
- and possibly a digital map providing some useful feature (terrain altitude, power attenuation, etc.) at each possible position.

In some applications, another useful source of information is provided by

- a map of constrained admissible displacements, for instance in the form of an indoor building map,

which particle methods can easily handle (map-matching). This Bayesian dynamical estimation problem is also called filtering, and its numerical implementation using particle methods, known as particle filtering, has been introduced by the target tracking community, which has already contributed to many of the most interesting algorithmic improvements and is still very active, and has found applications in target tracking, integrated navigation, points and objects tracking in video sequences, mobile robotics, wireless communications, ubiquitous computing and ambient intelligence, sensor networks, etc.

ASPI is contributing (or has contributed recently) to several applications of particle filtering in positioning, navigation and tracking, such as geolocalisation and tracking in a wireless network, terrain-aided navigation, and data fusion for indoor localisation.

4.2. Rare event simulation

Another application domain of particle methods, or interacting Monte Carlo methods, that ASPI has decided to focus on is the estimation of the small probability of a rare but critical event, in complex dynamical systems. This is a crucial issue in industrial areas such as nuclear power plants, food industry, telecommunication networks, finance and insurance industry, air traffic management, etc.

In such complex systems, analytical methods cannot be used, and naive Monte Carlo methods are clearly inefficient to estimate accurately very small probabilities. Besides importance sampling, an alternate widespread technique consists in multilevel splitting, where trajectories going towards the critical set are given offsprings, thus increasing the number of trajectories that eventually reach the critical set. This approach not only makes it possible to estimate the probability of the rare event, but also provides realizations of the random trajectory, given that it reaches the critical set, i.e. provides realizations of typical critical trajectories, an important feature that methods based on importance sampling usually miss.

ASPI is contributing (or has contributed recently) to several applications of multilevel splitting for rare event simulation, such as risk assessment in air traffic management, detection in sensor networks, and protection of digital documents.
4. Application Domains

4.1. Application Domains

Our abilities in probability and statistics apply naturally to industry in particular in studies of dependability and safety.

An illustrative example which gathers all the topics of team is a collaboration started in May 2010 with Thales Optronique on the subject of optimization of the maintenance of a digital camera equipped with HUMS (Health Unit Monitoring Systems). This subject is very interesting for us because it combines many aspects of our project. Classification tools will be used to select significant variables as the first step in the modeling of a digital camera. The model will then be analysed and estimated in order to optimize the maintenance.

A second example concerns the optimization of the maintenance date for an aluminum metallic structure subject to corrosion. It is a structure of strategic ballistic missile that is stored in a nuclear submarine missile launcher in peace-time and inspected with a given periodicity. The requirement for security on this structure is very strong. The mechanical stress exerted on the structure depends on its thickness. It is thus crucial to control the evolution of the thickness of the structure over time, and to intervene before the break.

A third example is the minimization of the acoustic signature of a submarine. The submarine has to chose its trajectory in order to minimize at each time step its observability by a surface ship following an unknown random trajectory.

But the spectrum of applications of the topics of the team is larger and may concern many other fields. Indeed non parametric and semi-parametric regression methods can be used in biometry, econometrics or engineering for instance. Gene selection from microarray data and text categorization are two typical application domains of dimension reduction among others. We had for instance the opportunity via the scientific program PRIMEQUAL to work on air quality data and to use dimension reduction techniques as principal component analysis (PCA) or positive matrix factorization (PMF) for pollution sources identification and quantization.
4. Application Domains

4.1. Introduction

In this section, the problems we are faced with vibration-based monitoring and within our two major application domains are briefly described.

4.2. Vibrations-based monitoring

Detecting and localizing damages for monitoring the integrity of structural and mechanical systems is a topic of growing interest, due to the aging of many engineering constructions and machines and to increased safety norms. Many current approaches still rely on visual inspections or local non-destructive evaluations performed manually. This includes acoustic, ultrasonic, radiographic or eddy-current methods; magnet or thermal field techniques, ... These experimental approaches assume an a priori knowledge and the accessibility of a neighborhood of the damage location. Automatic global vibration-based monitoring techniques have been recognized to be useful alternatives to those local evaluations [31]. However this has led to actual damage monitoring systems only in the field of rotating machines.

A common feature of the structures to be monitored (e.g. civil engineering structures subject to hurricanes or earthquakes, but also swell, wind and rain; aircrafts subject to strength and turbulences, ...) is the following. These systems are subject to both fast and unmeasured variations in their environment and small slow variations in their vibrating characteristics. The available data (measurements from e.g. strain gauges or accelerometers) do not separate the effects of the external forces from the effect of the structure. The external forces vary more rapidly than the structure itself (fortunately!), damages or fatigues on the structure are of interest, while any change in the excitation is meaningless. Expert systems based on a human-like exploitation of recorded spectra can hardly work in such a case: the changes of interest (1% in eigenfrequencies) are visible neither on the signals nor on their spectra. A global health monitoring method must rather rely on a model that will help in discriminating between the two mixed causes of the changes that are contained in the measurements.

Classical modal analysis and vibration monitoring methods basically process data registered either on test beds or under specific excitation or rotation speed conditions. However there is a need for vibration monitoring algorithms devoted to the processing of data recorded in-operation, namely during the actual functioning of the considered structure or machine, without artificial excitation, speeding down or stopping.

Health monitoring techniques based on processing vibration measurements basically handle two types of characteristics: the structural parameters (mass, stiffness, flexibility, damping) and the modal parameters (modal frequencies, and associated damping values and mode-shapes); see [35] and references therein. A central question for monitoring is to compute changes in those characteristics and to assess their significance. For the frequencies, crucial issues are then: how to compute the changes, to assess that the changes are significant, to handle correlations among individual changes. A related issue is how to compare the changes in the frequencies obtained from experimental data with the sensitivity of modal parameters obtained from an analytical model. Furthermore, it has been widely acknowledged that, whereas changes in frequencies bear useful information for damage detection, information on changes in (the curvature of) mode-shapes is mandatory for performing damage localization. Then, similar issues arise for the computation and the significance of the changes. In particular, assessing the significance of (usually small) changes in the mode-shapes, and handling the (usually high) correlations among individual mode-shape changes are still considered as open questions [35], [31].
Controlling the computational complexity of the processing of the collected data is another standard monitoring requirement, which includes a limited use of an analytical model of the structure. Moreover, the reduction from the analytical model to the experimental model (truncated modal space) is known to play a key role in the success of model-based damage detection and localization.

The approach which we have been developing, based on the foundations in modules 3.2 – 3.5, aims at addressing all the issues and overcoming the limitations above.

4.3. Civil engineering

Civil engineering is a currently renewing scientific research area, which can no longer be restricted to the single mechanical domain, with numerical codes as its central focus. Recent and significant advances in physics and physical chemistry have improved the understanding of the detailed mechanisms of the constitution and the behavior of various materials (see e.g. the multi-disciplinary general agreement CNRS-Lafarge). Moreover, because of major economical and societal issues, such as durability and safety of infrastructures, buildings and networks, civil engineering is evolving towards a multi-disciplinary field, involving in particular information sciences and technologies and environmental sciences.

These last ten years, monitoring the integrity of the civil infrastructure has been an active research topic, including in connected areas such as automatic control, for mastering either the aging of the bridges, as in America (US, Canada) and Great Britain, or the resistance to seismic events and the protection of the cultural heritage, as in Italy and Greece. The research effort in France seems to be more recent, maybe because a tendency of long term design without fatigue oriented inspections, as opposite to less severe design with planned mid-term inspections. One of the current thematic priorities of the Réseau de Génie Civil et Urbain (RGCU) is devoted to constructions monitoring and diagnostics. The picture in Asia (Japan, and also China) is somewhat different, in that the demand for automatic data processing for global SHM systems is much higher, because recent or currently built bridges are equipped with hundreds if not thousands of sensors, in particular the Hong Kong-Shenzen Western Corridor and Stonecutter Bridge projects.

Among the challenges for vibration-based bridges health monitoring, two major issues are the different kinds of (non measured) excitation sources and the environmental effects [36]. Typically the traffic on and under the bridge, the wind and also the rain, contribute to excite the structure, and influence the measured dynamics. Moreover, the temperature is also known to affect the eigenfrequencies and mode-shapes, to an extent which is significant w.r.t. the deviations to be monitored.

4.4. Aeronautics

The aging of aerospace structures is a major current concern of civilian and military aircraft operators. Another key driving factor for SHM is to increase the operation and support efficiency of an air vehicle fleet. A SHM system is viewed as a component of a global integrated vehicle health management (IVHM) system. An overview of the users needs can be found in [28].

Improved safety and performance and reduced aircraft development and operating costs are other major concerns. One of the critical design objectives is to clear the aircraft from unstable aero-elastic vibrations (flutter) in all flight conditions. This requires a careful exploration of the dynamical behavior of the structure subject to vibration and aero-servo-elastic forces. This is achieved via a combination of ground vibration tests and in-flight tests. For both types of tests, various sensors data are recorded, and modal analyses are performed. Important challenges of the in-flight modal analyses are the limited choices for measured excitation inputs, and the presence of unmeasured natural excitation inputs (turbulence). A better exploitation of flight test data can be achieved by using output-only system identification methods, which exploits data recorded under natural excitation conditions (e.g., turbulent), without resorting to artificial control surface excitation and other types of excitation inputs [10].
A crucial issue is to ensure that the newly designed airplane is stable throughout its operating range. A critical instability phenomenon, known under the name of “aero-elastic flutter, involves the unfavorable interaction of aerodynamic, elastic, and inertia forces on structures to produce an unstable oscillation that often results in structural failure” [33]. For preventing from this phenomenon, the airplane is submitted to a flight flutter testing procedure, with incrementally increasing altitude and airspeed. The problem of predicting the speed at which flutter can occur is usually addressed with the aid of identification methods achieving modal analysis from the in-flight data recorded during these tests. The rationale is that the damping coefficient reflects the rate of increase or decrease in energy in the aero-servo-elastic system, and thus is a relevant measure of stability. Therefore, while frequencies and mode-shapes are usually the most important parameters in structural analysis, the most critical ones in flutter analysis are the damping factors, for some critical modes. The mode-shapes are usually not estimated for flutter testing.

Until the late nineties, most approaches to flutter clearance have led to data-based methods, processing different types of data. A combined data-based and model-based method has been introduced recently under the name of flutterometer. Based on an aero-elastic state-space model and on frequency-domain transfer functions extracted from sensor data under controlled excitation, the flutterometer computes on-line a robust flutter margin using the $\mu$-method for analyzing the worst case effects of model uncertainty. In recent comparative evaluations using simulated and real data [30], [34], several data-based methods are shown to fail in accurately predicting flutter when using data from low speed tests, whereas the flutterometer turns out not to converge to the true flutter speed during envelope expansion, due to inherent conservative predictions.

Algorithms achieving the on-line in-flight exploitation of flight test data are expected to allow a more direct exploration of the flight domain, with improved confidence and reduced costs. Among other challenges, one important issue to be addressed on-line is the flight flutter monitoring problem, stated as the problem of monitoring some specific damping coefficients. On the other hand, it is known, e.g. from Cramer-Rao bounds, that damping factors are difficult to estimate accurately. For improving the estimation of damping factors, and moreover for achieving this in real-time during flight tests, one possible although unexpected route is to rely on detection algorithms able to decide whether some damping factor decreases below some critical value or not. The rationale is that detection algorithms usually have a much shorter response time than identification algorithms.
3. Application Domains

3.1. Application domains

- Option pricing and hedging
- Calibration of financial models
- Portfolio optimization
- Risk management
- Market microstructure
- Insurance-reinsurance optimization policy
- Insider modeling, asymmetry of information
4. Application Domains

4.1. Application: uncertainties management

Our theoretical works are motivated by and find natural applications to real-world problems in a general frame generally referred to as uncertainty management, that we describe now.

Since a few decades, modeling has gained an increasing part in complex systems design in various fields of industry such as automobile, aeronautics, energy, etc. Industrial design involves several levels of modeling: from behavioural models in preliminary design to finite-elements models aiming at representing sharply physical phenomena. Nowadays, the fundamental challenge of numerical simulation is in designing physical systems while saving the experimentation steps.

As an example, at the early stage of conception in aeronautics, numerical simulation aims at exploring the design parameters space and setting the global variables such that target performances are satisfied. This iterative procedure needs fast multiphysical models. These simplified models are usually calibrated using high-fidelity models or experiments. At each of these levels, modeling requires control of uncertainties due to simplifications of models, numerical errors, data imprecisions, variability of surrounding conditions, etc.

One dilemma in the design by numerical simulation is that many crucial choices are made very early, and thus when uncertainties are maximum, and that these choices have a fundamental impact on the final performances.

Classically, coping with this variability is achieved through model registration by experimenting and adding fixed margins to the model response. In view of technical and economical performance, it appears judicious to replace these fixed margins by a rigorous analysis and control of risk. This may be achieved through a probabilistic approach to uncertainties, that provides decision criteria adapted to the management of unpredictability inherent to design issues.

From the particular case of aircraft design emerge several general aspects of management of uncertainties in simulation. Probabilistic decision criteria, that translate decision making into mathematical/probabilistic terms, require the following three steps to be considered [50]:

1. build a probabilistic description of the fluctuations of the model’s parameters (Quantification of uncertainty sources),
2. deduce the implication of these distribution laws on the model’s response (Propagation of uncertainties),
3. and determine the specific influence of each uncertainty source on the model’s response variability (Sensitivity Analysis).

The previous analysis now constitutes the framework of a general study of uncertainties. It is used in industrial contexts where uncertainties can be represented by random variables (unknown temperature of an external surface, physical quantities of a given material, ... at a given fixed time). However, in order for the numerical models to describe with high fidelity a phenomenon, the relevant uncertainties must generally depend on time or space variables. Consequently, one has to tackle the following issues:

- **How to capture the distribution law of time (or space) dependent parameters, without directly accessible data?** The distribution of probability of the continuous time (or space) uncertainty sources must describe the links between variations at neighbor times (or points). The local and global regularity are important parameters of these laws, since it describes how the fluctuations at some time (or point) induce fluctuations at close times (or points). The continuous equations representing the studied phenomena should help to propose models for the law of the random fields. Let us notice that interactions between various levels of modeling might also be used to derive distributions of probability at the lowest one.
The navigation between the various natures of models needs a kind of metric which could mathematically describe the notion of granularity or fineness of the models. Of course, the local regularity will not be totally absent of this mathematical definition.

All the various levels of conception, preliminary design or high-fidelity modelling, require registrations by experimentation to reduce model errors. This calibration issue has been present in this frame since a long time, especially in a deterministic optimization context. The random modeling of uncertainty requires the definition of a systematic approach. The difficulty in this specific context is: statistical estimation with few data and estimation of a function with continuous variables using only discrete setting of values.

Moreover, a multi-physical context must be added to these questions. The complex system design is most often located at the interface between several disciplines. In that case, modeling relies on a coupling between several models for the various phenomena and design becomes a multidisciplinary optimization problem. In this uncertainty context, the real challenge turns robust optimization to manage technical and economical risks (risk for non-satisfaction of technical specifications, cost control).

We participate in the uncertainties community through several collaborative research projects (ANR and Pôle SYSTEM@TIC), and also through our involvement in the MASCOT-NUM research group (GDR of CNRS). In addition, we are considering probabilistic models as phenomenological models to cope with uncertainties in the DIGITEO ANIFRAC project. As explained above, we focus on essentially irregular phenomena, for which irregularity is a relevant quantity to capture the variability (e.g. certain biomedical signals, terrain modeling, financial data, etc.). These will be modeled through stochastic processes with prescribed regularity.

4.2. Design of complex systems

Figure 3. Coupling uncertainty between heterogeneous models
The design of a complex (mechanical) system such as aircraft, automobile or nuclear plant involves numerical simulation of several interacting physical phenomena: CFD and structural dynamics, thermal evolution of a fluid circulation, ... For instance, they can represent the resolution of coupled partial differential equations using finite element method. In the framework of uncertainty treatment, the studied “phenomenological model” is a chaining of different models representing the various involved physical phenomena. As an example, the pressure field on an aircraft wing is the result of both aerodynamic and structural mechanical phenomena. Let us consider the particular case of two models of partial differential equations coupled by limit conditions. The direct propagation of uncertainties is impossible since it requires an exploration and then, many calls to costly models. As a solution, engineers use to build reduced-order models: the complex high-fidelity model is substituted with a CPU less costly model. The uncertainty propagation is then realized through the simplified model, taking into account the approximation error (see [46]).

Interactions between the various models are usually explicited at the finest level (cf. Fig. 3). How may this coupling be formulated when the fine structures of exchange have disappeared during model reduction? How can be expressed the interactions between models at different levels (in a multi-level modeling)? The ultimate question would be: how to choose the right level of modeling with respect to performance requirements?

In the multi-physical numerical simulation, two kinds of uncertainties then coexist: the uncertainty due to substitution of high-fidelity models with approximated reduced-order models, and the uncertainty due to the new coupling structure between reduced-order models.

According to the previous discussion, the uncertainty treatment in a multi-physical and multi-level modeling implies a large range of issues, for instance numerical resolutions of PDE (which do not enter into the research topics of Regularity). Our goal is to contribute to the theoretical arsenal that allows to fly among the different levels of modeling (and then, among the existing numerical simulations). We will focus on the following three axes:

- In the case of a phenomenon represented by two coupled partial differential equations whose resolution is represented by reduced-order models, how to define a probabilistic model of the coupling errors? In connection with our theoretical development, we plan to characterize the regularity of this error in order to quantify its distribution. This research axis is supported by an ANR grant (OPUS project).

- The multi-level modeling assumes the ability to choose the right level of details for the models in adequacy to the goals of the study. In order to do that, a rigorous mathematical definition of the notion of model fineness/granularity would be very helpful. Again, a precise analysis of the fine regularity of stochastic models is expected to give elements toward a precise definition of granularity. This research axis is supported by a a PÂ’e SYSTEM@TIC grant (EHPOC project), and also by a collaboration with EADS.

- Some fine characteristics of the phenomenological model may be used to define the probabilistic behaviour of its variability. The action of modeling a phenomena can be seen as an interpolation issue between given observations. This interpolation can be driven by physical evolution equations or fine analytical description of the physical quantities. We are convinced that Hölder regularity is an essential parameter in that context, since it captures how variations at a given point induce variations at its neighbors. Stochastic processes with prescribed regularity (see section 3.3) have already been used to represent various fluctuating phenomena: Internet traffic, financial data, ocean floor. We believe that these models should be relevant to describe solutions of PDE perturbed by uncertain (random) coefficients or limit conditions. This research axis is supported by a PÂ’e SYSTEM@TIC grant (CSDL project).

4.3. Biomedical Applications

ECG analysis and modeling
ECG and signals derived from them are an important source of information in the detection of various pathologies, including e.g. congestive heart failure, arrhythmia and sleep apnea. The fact that the irregularity of ECG bears some information on the condition of the heart is well documented (see e.g. the web resource http://www.physionet.org ). The regularity parameters that have been studied so far are mainly the box and regularization dimensions, the local Hölder exponent and the multifractal spectrum \[ 53 \], \[ 55 \]. These have been found to correlate well with certain pathologies in some situations. From a general point of view, we participate in this research area in two ways.

- First, we use refined regularity characterizations, such as the regularization dimension, 2-microlocal analysis and advanced multifractal spectra for a more precise analysis of ECG data. This requires in particular to test current estimation procedures and to develop new ones.
- Second, we build stochastic processes that mimic in a faithful way some features of the dynamics of ECG. For instance, the local regularity of RR intervals, estimated in a parametric way based on a modeling by an mBm, displays correlations with the amplitude of the signal, a feature that seems to have remained unobserved so far \[ 3 \]. In other words, RR intervals behave as SRP. We believe that modeling in a simplified way some aspects of the interplay between the sympathetic and parasympathetic systems might lead to an SRP, and to explain both this self-regulating property and the reasons behind the observed multifractality of records. This will open the way to understanding how these properties evolve under abnormal behaviour.

**Pharmacodynamics and patient drug compliance**

Poor adherence to treatment is a worldwide problem that threatens efficacy of therapy, particularly in the case of chronic diseases. Compliance to pharmacotherapy can range from 5% to 90%. This fact renders clinical tested therapies less effective in ambulatory settings. Increasing the effectiveness of adherence interventions has been placed by the World Health Organization at the top list of the most urgent needs for the health system. A large number of studies have appeared on this new topic in recent years \[ 67 \], \[ 66 \]. In collaboration with the pharmacy faculty of Montréal university, we consider the problem of compliance within the context of multiple dosing. Analysis of multiple dosing drug concentrations, with common deterministic models, is usually based on patient full compliance assumption, i.e., drugs are administered at a fixed dosage. However, the drug concentration-time curve is often influenced by the random drug input generated by patient poor adherence behaviour, inducing erratic therapeutic outcomes. Following work already started in Montréal \[ 60 \], \[ 61 \], we consider stochastic processes induced by taking into account the random drug intake induced by various compliance patterns. Such studies have been made possible by technological progress, such as the “medication event monitoring system”, which allows to obtain data describing the behaviour of patients.

We use different approaches to study this problem: statistical methods where enough data are available, model-based ones in presence of qualitative description of the patient behaviour. In this latter case, piecewise deterministic Markov processes (PDP) seem a promising path. PDP are non-diffusion processes whose evolution follows a deterministic trajectory governed by a flow between random time instants, where it undergoes a jump according to some probability measure \[ 49 \]. There is a well-developed theory for PDP, which studies stochastic properties such as extended generator, Dynkin formula, long time behaviour. It is easy to cast a simplified model of non-compliance in terms of PDP. This has allowed us already to obtain certain properties of interest of the random concentration of drug \[ 40 \]. In the simplest case of a Poisson distribution, we have obtained rather precise results that also point to a surprising connection with infinite Bernouilli convolutions \[ 29 \], \[ 13 \], \[ 12 \]. Statistical aspects remain to be investigated in the general case.
4. Application Domains

4.1. Application Domains

TOSCA is interested in developing stochastic models and probabilistic numerical methods. Our present motivations come from Finance, Neuroscience and Biology, Fluid Mechanics and Meteorology, Chemical Kinetics, Diffusions in random media, Transverse problems, Software and Numerical experiments.

Finance  For a long time now TOSCA has collaborated with researchers and practitioners in various financial institutions and insurance companies. We are particularly interested in calibration problems, risk analysis (especially model risk analysis), optimal portfolio management, Monte Carlo methods for option pricing and risk analysis, asset and liabilities management. We also work on the partial differential equations related to financial issues, for example the stochastic control Hamilton–Jacobi–Bellman equations. We study existence, uniqueness, qualitative properties and appropriate deterministic or probabilistic numerical methods. At the moment we pay special attention to the financial consequences induced by modelling errors and calibration errors on hedging strategies and portfolio management strategies.

Neuroscience and Biology  The interest of TOSCA in biology is developing in three main directions: neuroscience, molecular dynamics and population dynamics. In neuroscience, stochastic methods are developed to analyze stochastic resonance effects and to solve inverse problems. For example, we are studying probabilistic interpretations and Monte Carlo methods for divergence form second-order differential operators with discontinuous coefficients, motivated by the 3D MEG inverse problem. Our research in molecular dynamics focuses on the development of Monte Carlo methods for the Poisson-Boltzmann equation which also involves a divergence form operator, and of original algorithms to construct improved simulation techniques for protein folding or interaction. Finally, our interest in population dynamics comes from ecology, evolution and genetics. For example, we are studying the emergence of diversity through the phenomenon of evolutionary branching in adaptive dynamics. Some collaborations in biostatistics on cancer problems are also being initiated.

Fluid Mechanics and Meteorology  In Fluid Mechanics we develop probabilistic methods to solve vanishing vorticity problems and to study the behavior of complex flows at the boundary, and their interaction with the boundary. We elaborate and analyze stochastic particle algorithms. Our studies concern the convergence analysis of these methods on theoretical test cases and the design of original schemes for applicative cases. A first example concerns the micro-macro model of polymeric fluids (the FENE model). A second example concerns Pope’s Lagrangian modelling of turbulent flows, motivated by the problem of modelling and computing characteristic properties of the local wind activity in areas where windmills are built. Our goal is to estimate local energy resources which are subject to meteorological randomness by combining large scale wind models and small scale Monte Carlo techniques, and to simulate management strategies of wind resources.

Chemical Kinetics  The TOSCA team is studying coagulation and fragmentation models, that have numerous areas of applications (polymerization, aerosols, cement industry, copper industry, population dynamics...). Our current motivation comes from the industrial copper crushers in Chile. We aim to model and calibrate the process of fragmentation of brass particles of copper in industrial crushers, in order to improve their efficiency at a low cost.

Diffusions in random media  A random medium is a material with a lot of heterogeneity which can be described only statistically. Typical examples are fissured porous media within rocks of different types, turbulent fluids or unknown or deficient materials in which polymers evolve or waves propagate. For the last few years, the TOSCA team has been collaborating with the Geophysics
community on problems related to underground diffusions, especially those which concern waste transport or oil extraction. We are extending our previous results on the simulation of diffusion processes generated by divergence form operators with discontinuous coefficients. Such an operator appears for example in the Darcy law for the behavior of a fluid in a porous media. We are also developing another class of Monte Carlo methods to simulate diffusion phenomena in discontinuous media.

Transverse problems Several of the topics of interest of TOSCA do not only concern a single area of application. This is the case in particular for long time simulation methods of nonlinear McKean-Vlasov PDEs, the problem of simulation of multivalued models, variance reduction techniques or stochastic partial differential equations. For example, multivalued processes have applications in random mechanics or neuroscience, and variance reduction techniques have applications in any situation where Monte Carlo methods are applicable.

Software, numerical experiments TOSCA is interested in designing algorithms of resolution of specific equations in accordance with the needs of practitioners. We benefit from our strong experience of the programming of probabilistic algorithms of various architectures including intensive computation architectures. In particular, our activity will concern the development of grid computing techniques to solve large dimensional problems in Finance. We are also interested in intensively comparing various Monte Carlo methods for PDEs and in the development of open source libraries for our numerical methods in Fluid Mechanics, Meteorology, MEG or Chemical Kinetics.