INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

# *Project-Team corida*

# *Robust control of infinite dimensional systems and applications*

*Nancy - Grand Est*

Theme : Modeling, Optimization, and Control of Dynamic Systems

Activity Report

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# 2. Overall Objectives

## 2.1. Overall Objectives

CORIDA is a team labeled by INRIA, by CNRS and by University Henri Poincaré, via the Institut Élie Cartan of Nancy (UMR 7502 CNRS-INRIA-UHP-INPL-University of Nancy 2). The main focus of our research is the robust control of systems governed by partial differential equations (called PDE's in the sequel). A special attention is devoted to systems with a hybrid dynamics such as the fluid-structure interactions. The equations modeling these systems couple either partial differential equations of different types or finite dimensional systems and infinite dimensional systems. We mainly consider inputs acting on the boundary or which are localized in a subset of the domain.

Infinite dimensional systems theory is motivated by the fact that a large number of mathematical models in applied sciences are given by evolution partial differential equations. Typical examples are the transport, heat or wave equations, which are used as mathematical models in a large number of problems in physics, chemistry, biology or finance. In all these cases the corresponding state space is infinite dimensional. The understanding of these systems from the point of view of control theory is an important scientific issue which has received a considerable attention during the last decades. Let us mention here that a basic question like the study of the controllability of infinite dimensional linear systems requires sophisticated techniques such as non harmonic analysis (cf. Russell [83]), multiplier methods (cf. Lions [79]) or micro-local analysis techniques (cf. Bardos–Lebeau–Rauch [70]). Like in the case of finite dimensional systems, the study of controllability should be only the starting point of the study of important and more practical issues like feedback optimal control or robust control. It turns out that most of these questions are open in the case of infinite dimensional systems. Consequently, our aim is to develop tools for the robust control of infinite dimensional systems. More precisely, given an infinite dimensional system one should be able to answer two basic questions:

1. Study the existence of a feedback operator with robustness properties.
2. Find an algorithm allowing the approximate computation of this feedback operator.

The answer to question 1 above requires the study of infinite dimensional Riccati operators and it is a difficult theoretical question. The answer to question 2 depends on the sense of the word “approximate”. In our meaning “approximate” means “convergence”, i.e., that we look for approximate feedback operators converging to the exact one when the discretization step tends to zero. From the practical point of view this means that our control laws should give good results if we use a large number of state variables. This fact is no longer a practical limitation of such an approach, at least in some important applications where powerful computers are now available. We intend to develop a methodology applicable to a large class of applications.

## 2.2. Highlights

Some noticeable events of the year 2010 for our team are:

- The defense of the HDR [14] of Mario Sigalotti.
- The defense of the Phd Thesis [13] of P. Klein (supervised by X. Antoine).
- The defense of the Phd Thesis [11] of N. Cîndea (supervised by M. Tucsnak).
- The contracts with ONERA (FRAE) and EADS (see the section Contrats with Industry for details).

# 3. Scientific Foundations

## 3.1. Analysis and control of fluids and of fluid-structure interactions

**Participants:** Thomas Chambrion, Antoine Henrot, Alexandre Munnier, Lionel Rosier, Jean-François Scheid, Mario Sigalotti, Takéo Takahashi, Marius Tucsnak, Jean-Claude Vivalda.

The problems we consider are modeled by the Navier-Stokes, Euler or Korteweg de Vries equations (for the fluid) coupled to the equations governing the motion of the solids. One of the main difficulties of this problem comes from the fact that the domain occupied by the fluid is one of the unknowns of the problem. We have thus to tackle a *free boundary problem*.

The control of fluid flows is a major challenge in many applications: aeronautics, pollution issues, regulation of irrigation channels or of the flow in pipelines, etc. All these problems cannot be easily reduced to finite dimensional models so a methodology of analysis and control based on PDE's is an essential issue. In a first approximation the motion of fluid and of the solids can be decoupled. The most used models for an incompressible fluid are given by the Navier-Stokes or by the Euler equations.

The optimal open loop control approach of these models has been developed from both the theoretical and numerical points of view. Controllability issues for the equations modeling the fluid motion are by now well understood (see, for instance, Imanuvilov [76] and the references therein). The feedback control of fluid motion has also been recently investigated by several research teams (see, for instance Barbu [69] and references therein) but this field still contains an important number of open problems (in particular those concerning observers and implementation issues). One of our aims is to develop efficient tools for computing feedback laws for the control of fluid systems.

In real applications the fluid is often surrounded by or it surrounds an elastic structure. In the above situation one has to study fluid-structure interactions. This subject has been intensively studied during the last years, in particular for its applications in noise reduction problems, in lubrication issues or in aeronautics. In this kind of problems, a PDE's system modeling the fluid in a cavity (Laplace equation, wave equation, Stokes, Navier-Stokes or Euler systems) is coupled to the equations modeling the motion of a part of the boundary. The difficulties of this problem are due to several reasons such as the strong nonlinear coupling and the existence of a free boundary. This partially explains the fact that applied mathematicians have only recently tackled these problems from either the numerical or theoretical point of view. One of the main results obtained in our project concerns the global existence of weak solutions in the case of a two-dimensional Navier–Stokes fluid (see [8]). Another important result gives the existence and the uniqueness of strong solutions for two or three-dimensional Navier–Stokes fluid (see [9]). In that case, the solution exists as long as there is no contact between rigid bodies, and for small data in the three-dimensional case.

In [4], we study the large time behavior of solutions of a parabolic equation coupled with an ordinary differential equation. This system is a simplified $N$-dimensional model for the interactive motion of a rigid body (a ball) immersed in a viscous fluid. After proving the existence and uniqueness of a strong global in time solution, we compute the first term in the asymptotic development of solutions. We prove that the asymptotic profile of the fluid is the heat kernel with an appropriate total mass. The $L^\infty$ estimates we get allow us to describe the asymptotic trajectory of the center of mass of the rigid body as well.

The numerical methods used for computing the solutions of fluid or fluid structure problems in a direct setting (i.e., with given inputs) considerably progressed during the last years. In our project, we have proposed in [6] an original numerical scheme to discretize the equations of motion for the system composed by a viscous incompressible fluid and several rigid bodies. One important characteristic of this scheme is that we use only a fixed mesh for the whole system, and therefore we do not need to remesh at some steps like for instance in the case of ALE methods. We have also developed two codes (in Matlab and in Scilab) based on our numerical scheme.

Another topic of great interest is the control of the interface of two fluids (typically water and air) by using as input the velocity of a moving wall which is a part of the boundary. One of the most popular models for this problem is given by the shallow water equations (Saint Venant equations) which neglect the dispersive effects. The controllability of several important systems governed by this type of equations has received a considerable attention during the last decade. Let us mention here the important work by Coron [71]. If dispersive effects are considered, the relevant model is given by the Korteweg de Vries equation. The first work on the control of this equation goes back to Russell and Zhang (see [84]). An important advance in the study of this problem has been achieved in the work of Rosier [82] where, for the first time, the influence of the length of the channel has been precisely investigated.

## 3.2. Frequency domain methods for the analysis and control of systems governed by PDE's

**Participants:** Xavier Antoine, Pauline Klein, Bruno Pinçon, Karim Ramdani, Bertrand Thierry.

We use frequency tools to analyze different types of problems. The first one concerns the control, the optimal control and the stabilization of systems governed by PDE's, and their numerical approximations. The second one concerns time-reversal phenomena, while the last one deals with numerical approximation of high-frequency scattering problems.

### *3.2.1. Control and stabilization for skew-adjoint systems*

The first area concerns theoretical and numerical aspects in the control of a class of PDE's. More precisely, in a semigroup setting, the systems we consider have a skew-adjoint generator. Classical examples are the wave, the Bernoulli-Euler or the Schrödinger equations. Our approach is based on an original characterization of exact controllability of second order conservative systems proposed by K. Liu [80]. This characterization can be related to the Hautus criterion in the theory of finite dimensional systems (cf. [74]). It provides for time-dependent problems exact controllability criteria **that do not depend on time, but depend on the frequency variable** conjugated to time. Studying the controllability of a given system amounts then to establishing uniform (with respect to frequency) estimates. In other words, the problem of exact controllability for the wave equation, for instance, comes down to a high-frequency analysis for the Helmholtz operator. This frequency approach has been proposed first by K. Liu for bounded control operators (corresponding to internal control problems), and has been recently extended to the case of unbounded control operators (and thus including boundary control problems) by L. Miller [81]. Using the result of Miller, K. Ramdani, T. Takahashi, M. Tucsnak have obtained in [5] a new spectral formulation of the criterion of Liu [80], which is valid for boundary control problems. This frequency test can be seen as an observability condition for packets of eigenvectors of the operator. This frequency test has been successfully applied in [5] to study the exact controllability of the Schrödinger equation, the plate equation and the wave equation in a square. Let us emphasize here that one further important advantage of this frequency approach lies in the fact that it can also be used for the analysis of space semi-discretized control problems (by finite element or finite differences). The estimates to be proved must then be uniform with respect to **both the frequency and the mesh size**.

In the case of finite dimensional systems one of the main applications of frequency domain methods consists in designing robust controllers, in particular of $H^\infty$ type. Obtaining the similar tools for systems governed by PDE's is one of the major challenges in the theory of infinite dimensional systems. The first difficulty which has to be tackled is that, even for very simple PDE systems, no method giving the parametrisation of all stabilizing controllers is available. One of the possible remedies consists in considering known families of stabilizing feedback laws depending on several parameters and in optimizing the $H^\infty$ norm of an appropriate transfer function with respect to this parameters. Such families of feedback laws yielding computationally tractable optimization problems are now available for systems governed by PDE's in one space dimension.

### *3.2.2. Time-reversal*

The second area in which we make use of frequency tools is the analysis of time-reversal for harmonic acoustic waves. This phenomenon described in Fink [72] is a direct consequence of the reversibility of the wave equation in a non dissipative medium. It can be used to **focus an acoustic wave** on a target through a complex and/or unknown medium. To achieve this, the procedure followed is quite simple. First, time-reversal mirrors are used to generate an incident wave that propagates through the medium. Then, the mirrors measure the acoustic field diffracted by the targets, time-reverse it and back-propagate it in the medium. Iterating the scheme, we observe that the incident wave emitted by the mirrors focuses on the scatterers. An alternative and more original focusing technique is based on the so-called D.O.R.T. method [73]. According to this experimental method, the eigenelements of the time-reversal operator contain important information on the propagation medium and on the scatterers contained in it. More precisely, the number of nonzero eigenvalues is exactly the number of scatterers, while each eigenvector corresponds to an incident wave that selectively focuses on each scatterer.

Time-reversal has many applications covering a wide range of fields, among which we can cite **medicine** (kidney stones destruction or medical imaging), **sub-marine communication** and **non destructive testing**. Let us emphasize that in the case of time-harmonic acoustic waves, time-reversal is equivalent to phase conjugation and involves the Helmholtz operator.

In [2], we proposed the first far field model of time reversal in the time-harmonic case.

### *3.2.3. Numerical approximation of high-frequency scattering problems*

This subject deals mainly with the numerical solution of the Helmholtz or Maxwell equations for open region scattering problems. This kind of situation can be met e.g. in radar systems in electromagnetism or in acoustics for the detection of underwater objects like submarines.

Two particular difficulties are considered in this situation

- the wavelength of the incident signal is small compared to the characteristic size of the scatterer,
- the problem is set in an unbounded domain.

These two problematics limit the application range of most common numerical techniques. The aim of this part is to develop new numerical simulation techniques based on microlocal analysis for modeling the propagation of rays. The importance of microlocal techniques in this situation is that it makes possible a local analysis both in the spatial and frequency domain. Therefore, it can be seen as a kind of asymptotic theory of rays which can be combined with numerical approximation techniques like boundary element methods. The resulting method is called the On-Surface Radiation Condition method.

## 3.3. Observability, controllability and stabilization in the time domain

**Participants:** Fatiha Alabau, Xavier Antoine, Thomas Chambrion, Antoine Henrot, Karim Ramdani, Mario Sigalotti, Marius Tucsnak, Jean-Claude Vivalda.

Controllability and observability have been set at the center of control theory by the work of R. Kalman in the 1960's and soon they have been generalized to the infinite-dimensional context. The main early contributors have been D.L. Russell, H. Fattorini, T. Seidman, R. Triggiani, W. Littman and J.-L. Lions. The latter gave the field an enormous impact with his book [78] , which is still a main source of inspiration for many researchers. Unlike in classical control theory, for infinite-dimensional systems there are many different (and not equivalent) concepts of controllability and observability. The strongest concepts are called exact controllability and exact observability, respectively. In the case of linear systems exact controllability is important because it guarantees stabilizability and the existence of a linear quadratic optimal control. Dually, exact observability guarantees the existence of an exponentially converging state estimator and the existence of a linear quadratic optimal filter. An important feature of infinite dimensional systems is that, unlike in the finite dimensional case, the conditions for exact observability are no longer independent of time. More precisely, for simple systems like a string equation, we have exact observability only for times which are large enough. For systems governed by other PDE's (like dispersive equations) the exact observability in arbitrarily small time has been only recently established by using new frequency domain techniques. A natural question is to estimate the energy required to drive a system in the desired final state when the control time goes to zero. This is a challenging theoretical issue which is critical for perturbation and approximation problems. In the finite dimensional case this issue has been first investigated in Seidman [85]. In the case of systems governed by linear PDE's some similar estimates have been obtained only very recently (see, for instance Miller [81]). One of the open problems of this field is to give sharp estimates of the observability constants when the control time goes to zero.

Even in the finite-dimensional case, despite the fact that the linear theory is well established, many challenging questions are still open, concerning in particular nonlinear control systems.

In some cases it is appropriate to regard external perturbations as unknown inputs; for these systems the synthesis of observers is a challenging issue, since one cannot take into account the term containing the unknown input into the equations of the observer. While the theory of observability for linear systems with unknown inputs is well established, this is far from being the case in the nonlinear case. A related active field of research is the uniform stabilization of systems with time-varying parameters. The goal in this case is to stabilize a control system with a control strategy independent of some signals appearing in the dynamics, i.e., to stabilize simultaneously a family of time-dependent control systems and to characterize families of control systems that can be simultaneously stabilized.

One of the basic questions in finite- and infinite-dimensional control theory is that of motion planning, i.e., the explicit design of a control law capable of driving a system from an initial state to a prescribed final one. Several techniques, whose suitability depends strongly on the application which is considered, have been and are being developed to tackle such a problem, as for instance the continuation method, flatness, tracking or optimal control. Preliminary to any question regarding motion planning or optimal control is the issue of controllability, which is not, in the general nonlinear case, solved by the verification of a simple algebraic criterion. A further motivation to study nonlinear controllability criteria is given by the fact that techniques developed in the domain of (finite-dimensional) geometric control theory have been recently applied successfully to study the controllability of infinite-dimensional control systems, namely the Navier–Stokes equations (see Agrachev and Sarychev [68]).

## 3.4. Implementation

This is a transverse research axis since all the research directions presented above have to be validated by giving control algorithms which are aimed to be implemented in real control systems. We stress below some of the main points which are common (from the implementation point of view) to the application of the different methods described in the previous sections.

For many infinite dimensional systems the use of co-located actuators and sensors and of simple proportional feed-back laws gives satisfying results. However, for a large class of systems of interest it is not clear that these feedbacks are efficient, or the use of co-located actuators and sensors is not possible. This is why a more general approach for the design of the feedbacks has to be considered. Among the techniques in finite dimensional systems theory those based on the solutions of infinite dimensional Riccati equation seem the most appropriate for a generalization to infinite dimensional systems. The classical approach is to approximate an LQR problem for a given infinite dimensional system by finite dimensional LQR problems. As it has been already pointed out in the literature this approach should be carefully analyzed since, even for some very simple examples, the sequence of feedbacks operators solving the finite dimensional LQR is not convergent. Roughly speaking this means that by refining the mesh we obtain a closed loop system which is not exponentially stable (even if the corresponding infinite dimensional system is theoretically stabilized). In order to overcome this difficulty, several methods have been proposed in the literature : filtering of high frequencies, multigrid methods or the introduction of a numerical viscosity term. We intend to first apply the numerical viscosity method introduced in Tcheougoué Tebou – Zuazua [86], for optimal and robust control problems.

# 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. [87]. 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. [77], 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/ .

# 5. New Results

## 5.1. Analysis and control of fluids and of fluid-structure interactions

**Participants:** Thomas Chambrion, Antoine Henrot, Alexandre Munnier, Yu Ning Liu, Jean-François Scheid, Erica Schwindt, Mario Sigalotti, Takéo Takahashi, Marius Tucsnak, Jean-Claude Vivalda, Jérôme Lohéac.

The study of a fluid-structure system depends on the nature of the fluid considered and in particular on the Reynolds number. We have split the new results of this section according to the viscosity of the fluid. The first part is devoted to the case of a viscous fluid. This is the case that has received more attention from mathematicians in the recent years. In the second part, we have put the results concerning an inviscid fluid. This case is more classical in Fluid Mechanics and could be more interesting to understand self-propelled motions which is one of the main goal of our work. In the last part, we have given some numerical results.

### *5.1.1. Incompressible viscous fluids*

- Collisions: Concerning the system composed by a rigid ball moving into a viscous incompressible fluid, there are still many open questions concerning the existence of shocks or contacts between rigid bodies. It was recently proved that there is no collision when there is only one body in a bounded (or partially bounded) two-dimensional cavity and for particuliar geometry. In [75], Hillairet (University of Toulouse) and Takahashi considered a similar geometry of a ball falling on a horizontal plane, but in 3D. They showed that for any weak solution of the corresponding system satisfying the energy inequality, the rigid ball never hits the plane in finite time. Then, using some symmetry result and considering once again some particular geometry, the same authors proved in [34] that in 3D, contact holds in finite time implying a blow-up of the strong solutions at the contact time.
- In [59] we gather an important number of recent results concerning the motion of rigid bodies in viscous incompressible fluids (particulate flows). This is, a s far as we know, the first presentation in book form of the state of the art in this emerging field.
- Control of biomimetic systems: In Sigalotti and Vivalda [46] the authors consider a finite-dimensional model for the motion of *ciliata*, coupling Newton's laws for the organism with the Stokes equations governing the surrounding fluid. We prove that such a system is generically controllable when the space of controlled velocity fields is at least three-dimensional. We also provide a complete characterization of controllable systems in the case in which the organism has a spherical shape. Finally, we offer a complete picture of controllable and non-controllable systems under the additional hypothesis that the organism and the fluid have densities of the same order of magnitude.

### *5.1.2. Ideal fluids*

- Motion of immersed rigid bodies: In [35] we prove the existence of strong solutions for a system modeling the motion of rigid bodies in an ideal (not necessarily irotational) fluid. The main novelty consists that we are able to tackle an arbitrary numbere of rigid bodies of arbitrary shape.
- Control of biomimetic systems: In [50], T. Chambrion and A. Munnier present a model of 2D shape changing swimming body in an ideal fluid. By applying some standard geometric control technics, they obtain tracking results.
- Detection of immersed moving solids: In [27], C. Conca, M. Malik (CMM, university of Santiago of Chile) and A. Munnier study whether it is possible to detect the position and velocity of a moving rigid body immersed in a fluid by measuring some data of the fluid flow. They show that detection is not always possible and that it depends upon some geometric properties of the solids.

### 5.1.3. Numerical Analysis and Numerical Simulations

We study the convergence of a characteristics method for the discretization of a fluid-rigid system with incompressible Navier-Stokes. The characteristics method we propose allows to deal with discontinuous density in the fluid and solid parts. A time discretized scheme is proposed in [44] and an convergence analysis is performed for a fully discretized method in [54].

### 5.1.4. Related problems

In [29], Feireisl (Academy of Sciences of the Czech Republic), Novotný (University of Toulon) and Takahashi apply the methods of homogenization to the full Navier-Stokes-Fourier system describing the motion of a general viscous, compressible, and heat conducting fluid. They study the asymptotic behavior of solutions in perforated domains with tiny holes, where the diameter of the holes is proportional to their mutual distance. As a limit system, they identify a porous medium type equation with a nonlinear Darcy's law.

## 5.2. Frequency tools for the analysis of PDE's

**Participants:** Xavier Antoine, Pauline Klein, Bruno Pinçon, Karim Ramdani, Bertrand Thierry, Marius Tucsnak.

Our contribution in this direction mainly concerns the numerical approximation of scattering problems.

- In the book chapter [58], we propose a review of recent numerical methods for solving high-frequency multiple acoustic scattering problems. The analysis covers recent developments for three families of approaches: Fourier series based methods, PDE's approaches and Integral Equations based techniques.
- In [21], Antoine et al. presents some theoretical and numerical investigations concerning the fast computation of an exterior wave field to a scatterer by the Beam Propagation Method (BPM).
- In [47] we obtain a new version of the Lebeau-Robbiano sufficient condition for null-controllability of parabolic type equation, obtaining sharp estimates of the control cost. Moreover, we show that, for particular geometries, this condition can be checked by using techniques inspires from number theory, instead of the previously used Carleman estimates.

## 5.3. Observability, controllability and stabilization in the time domain

**Participants:** Fatiha Alabau, Xavier Antoine, Thomas Chambrion, Antoine Henrot, Karim Ramdani, Lionel Rosier, Mario Sigalotti, Takéo Takahashi, Marius Tucsnak, Jean-Claude Vivalda, Ghislain Haine, Victor Mikhaylov, Roberto Guglielmi, Lixin Yu.

### 5.3.1. Control

- In [37] we study the genericity of some conditions issuing from the problem of controlling the bilinear Schrödinger equation. In particular, we prove that it is approximately controllable generically with respect to the control potential.
- We study in [28] the observability and controllability properties of time-discrete approximation schemes of diffusive systems. Assuming that the continuous system is observable, we prove uniform observability results for suitable time-discretization schemes within the class of filtered data.
- In [24], we give sufficient conditions under which the trajectories of a mechanical control system can track any curve on the configuration manifold. The tracking control laws obtained by our constructions depend on several parameters. By imposing suitable asymptotic conditions on such parameters, we construct algorithmically one-parameter tracking control laws.

### 5.3.2. Stabilization

- **Time-delay systems** In [40] we consider abstract second order evolution equations with unbounded feedback with constant delay. Sufficient and explicit conditions are derived that guarantee the exponential or polynomial stability. Some new examples fitting into the abstract framework are presented. In [67] we consider the wave equation with a time-varying delay term in the boundary condition in a bounded and smooth domain. We prove exponential stability of the solution, by introducing suitable energies and Lyapounov functionals. Such analysis is also extended to a nonlinear case. In [30] we consider abstract second order evolution equations with unbounded feedback with time-varying delay. We prove the exponential decay under some conditions by introducing an abstract Lyapunov functional. Our abstract framework is applied to the wave, to the beam and to the plate equations with boundary delays.
- **Abstract results** In two recent works, Ramdani, Tucsnak et al. proposed an iterative algorithm to solve initial data inverse problems for a class of linear evolution equations (including the wave, the plate, the Schrödinger and the Maxwell equations in a bounded domain) from bounded [36] or unbounded [42] observation on a finite time interval. Our method uses stabilization techniques to construct time-reversed observers in order to estimate the initial state.

  In [23], Badra (University of Pau) and Takahashi consider the stabilization of the system $y' = Ay + Bu$ where $A : \mathcal{D}(A) \to \mathcal{X}$ is the generator of an analytic semigroup and $B : \mathcal{U} \to [\mathcal{D}(A^*)]'$ is a quasi-bounded operator. They consider controls $u$ which are linear combination of a *finite* family $(v_1, ..., v_K)$. They show that if $(A^*, B^*)$ satisfies a unique continuation property and if $K$ is greater or equal to the maximum of the geometric multiplicities of the the unstable modes of $A$, then the system is generically stabilizable with respect to the family $(v_1, ..., v_K)$. With the same functional framework, they also prove the stabilizability of a class of nonlinear system when using feedback or dynamical controllers. They apply these results to stabilize the Navier–Stokes equations in 2D and in 3D by using boundary control with an optimal number of controllers.
- **Vibrating systems** In [18], we show that if a linear system is observable through a locally distributed (resp. boundary) observation, then any dissipative nonlinear feedback locally distributed (resp. active only on a part of the boundary) stabilize the system and we give quasi-optimal energy decay rates, under the optimal condition of geometric optics of Bardos-Lebau-Rauch (1992). Our results generalize previous results by Haraux (1989) and Ammari and Tucsnak (2001) for linear feedbacks.

  In [17], we establish sharp energy decay rates for both finite and infinite dimensional nonlinear damped vibrating systems. We prove optimality in the finite dimensional case, and establish lower energy estimates in the infinite dimensional case. We also give applications to discretized wave and Petrowsky equations.

  In [16], we establish lower energy estimates for nonlinearly damped wave equations in case of boundary and localized nonlinear dampings of wave equations.

  In [19], we study the stabilization of Bresse system, which models vibrations of a beam through three coupled wave equations. We establish stabilization of the full system by a single feedback control.

  In [57] we present a course on stabilization of hyperbolic equations given at a CIME session on Control of PDE's in Italy in July 2010, including well-known results, together with recent ones including nonlinear stabilization, memory-damping and stabilization of coupled systems by a reduced number of controls.
- **Switched systems** In [52] we obtain a converse Lyapunov theorem for the uniform exponential stability of switched systems on Banach spaces. In [31] and [26] we study the stabilizability of a switched systems (in finite or infinite dimension) for which the linear dynamics corresponding to some parameters is at most polynomially unstable. In the infinite-dimensional case, we consider the specific case of a network of strings. We recover stabilizability under some conditions ensuring that the actuators do not fail too often.

  In [43], a suitable LaSalle principle for continuous-time linear switched systems is used to characterize invariant sets and their associated switching laws. An algorithm to determine algebraically these invariants is proposed. Observability analysis of a flying capacitor converter is proposed as an illustration.

In [55], we investigate sufficient conditions for the convergence to zero of the trajectories of linear switched systems. We apply our result to the synthesis of an observer for the three-cell converter.

- **Approximation and sampling** In [39] we consider the wave equation on an interval of length 1 with an interior damping at $\xi$. In this work, we are interested in the finite difference space semi-discretization of the above system. We show that a filtering of high frequency modes allows to restore a quasi exponential decay of the discrete energy.

  In [20], we consider an observable continuous-time bilinear system and the discrete-time system obtained by sampling this continuous-time system. We show that under some conditions, the observability is preserved under this operation of sampling and we show also that it is possible to stabilize the discrete-time system through an observer.

# 6. Contracts and Grants with Industry

## 6.1. ANR

We continued in 2010 our activities connected to the existing ANR grants:

- CISIFS (Control of Fluid-structure Interactions), coordinated by Lionel Rosier and Takéo Takahashi: 90500 euros for 4 years (2009-2013);
- MICROWAVES (Microlocal Analysis and Numerical Methods for Wave Propagation), coordinated by Xavier Antoine: 103000 euros for 4 years (2009-2013);
- GAOS (Geometric Analysis of Optimal Shapes), with Antoine Henrot local coordinator: 83130 euros for 3 years (2009-2012);
- GCM (Geometric Control Methods), with Mario Sigalotti local coordinator: 129266 euros for 4 years (2009-2013).
- MOSICOB: this ANR project (2008-2011) is devoted to complex fluids and to fluid-structure interactions. Our work concerns mainly the analysis and simulation of vesicles in a fluid flow.
- ANR ARPEGE program ArHyCo (Since January 2009) is devoted to the stability analysis of hybrid systems with special attention to the observer-based control of multicell power converters;

## 6.2. FRAE (Fondation de Recherche pour l'Aéronautique et l'Espace)

In March 2010, Karim Ramdani obtained a 2 years funding from FRAE[3] to work on inverse problems in Aeronautics. The project involves two partners : INRIA Nancy Grand-Est (7 participants, from which 5 members of CORIDA) Êand ONERA Toulouse (4 participants).

## 6.3. EADS Foundation

We obtained a four years grant (2010-2014) of 147000 euros from EADS foundation. This project aims to develop new efficient numerical methods to solve electromagnetic scattering problems. Part of this grant is used to support the Phd of I. Zangré supervised by X. Antoine and C. Geuzaine (University of Liège). Y. Saad (university of Minneapolis) is also involved in this project.

[3] Fondation de Recherche pour l'Aéronautique et l'Espace : http://www.fnrae.org/

# 7. Other Grants and Activities

## 7.1. National Initiatives

### *7.1.1. Administrative responsibilities*

- Henrot is the head of Fédération Charles Hermite (FR CNRS 3198) which is a Federation of four scientific units: CRAN (Research Center for Automatic Control), IECN (Institut Elie Cartan of Nancy), LMAM (Mathematical Center of research in Metz), LORIA ((Lorraine Laboratory of IT Research and its Application). He is also head of the “ANR blanc project" GAOS in Nancy.
- Tucsnak
  - Head of the Institut Élie Cartan de Nancy (IECN)
  - Member of the Scientific Council of UHP and at INRIA.
  - Member of the Executive Team and of the Project Committee of the INRIA Nancy-Grand Est Research Centre.
- Alabau is member of CNU, section 26.

### *7.1.2. National Projects*

- CPER (“Contrat Plan Etat Région”):
  - Serres, Sigalotti (leader),Vivalda, Chambrion and Munnier are in “Stabilité et Commande des Systèmes à Commutations”. This is project in the AOC theme, in collaboration with the Automatic Control team at CRAN, is devoted to the stabilization of hybrid systems arising in the domain of DC-DC converters.
  - Scheid, Takahashi (leader) and Tucsnak are in the project “Se propulser dans un fluide, analyse, contrôle et visualisation” (AOC theme), in collaboration with the INRIA team, ALICE.
- Our team is part of the GDR entitled “Fluid-Structure Interactions”.

## 7.2. European Initiatives

- Henrot is coordinating an application for an International Training Network (ITN - Marie Curie) in the FP7 Program of the European Union. The application involves 11 nodes in 7 European countries.
- Alabau is main coordinator for France of the GDRE CONEDP in Control of PDE between France and Italy.
- Alexandre Munnier, Takéo Takahashi, Marius Tucsnak are in a PHC project PESSOA with a group of IST (Portugal).
- Tucsnak is also involved in a Romanian-French project (Brancusi) with the University of Craiova, on *Controllability of coupled systems*.

## 7.3. International Initiatives

### *7.3.1. Projects*

Indo-French project (CEFIPRA) with the Tata Institute for Fundamental Research, Bangalore, on *Control of partial differential equations*;

#### 7.3.2. Phd co-supervision

- PhD student Roberto Guglielmi from University Tor Vergata, Roma, Italy is co-supervised by Alabau with, since october 2010.
- PhD student Erica Schwindt is co-supervised by Takahashi and Conca (CMM, university of Santiago of Chile).
- PhD student Imen Ellouze is co-supervised by Vivalda and Mohamed-Ali Hammami from the University of Sfax (Tunisia) (Phd defended in December 2010).

#### 7.3.3. Visits of Foreign researchers

Evans Harrell (Georgia Tech, Atlanta), Gérard Philippin (U. Laval, Québec), Ana Leonor Silvestre (IST Lisbon, Portugal), Pedro Antunes (Lisbon).

# 8. Dissemination

## 8.1. Animation of the scientific community

#### 8.1.1. Organization of Conferences

- Alabau
  - Opening Ceremony of the GDRE CONEDP on Control of PDE's, Institute Henri Poincaré, Paris with representatives of INSMI-CNRS, DERCI-CNRS, UP, and the Ministro Plenipotenziario of the italian Embassy in Paris and his first Counsellor (October 12th).
  - Conference on Control of PDE's, GDRE-CNRS-INDAM-UP, CIRM Luminy, co-organized with F. Boyer (University Aix Marseille I), J. Le Rousseau (University of Orléans), F. Ancona (University of Padova, Italy) (January 25-29).
- Henrot
  - Organization of a workshop “Geometric Analysis of Optimal Shapes" in Nancy in June 2010.
- Scheid, Tucsnak
  - With M. Jungers (CRAN): organization of the Workshop “Self-propelled motions in fluids: modeling, analysis and control" in Nancy, France (October 21-22).
- Takahashi
  - With Ana Leonor Silvestre (IST, Portugal): organization of the international conference “International Workshop in Fluid-Structure Interaction Problems”, Foz do Arelho (Portugal) (September 6-8).

#### 8.1.2. Invitations to international conferences and workshops

- Alabau
  - “Special session on Control of PDE's with nonlocal terms", Trimester IHP on Control of PDE's, (December 16-17, Paris).
  - “Controllbility of coupled systems", Trimester IHP on Control of PDE's (November 26, Paris).
  - Invitation for the full trimester IHP on Control of PDE's (October-December, Paris).

- Invitation to give a course on “Stabilization of hyperbolic equations", C.I.M.E. Organizers: P. Cannarsa and J.-M. Coron, http://php.math.unifi.it/users/cime/ (July 19-23, Cetraro, Italy).
- 7th edition of the Conference Euro-Maghreb, (May 30-June 3, Annaba, Algeria).
- 8th AIMS Conference, (May 25-28, Dresden, Germany).

- Antoine
  - Workshop "Computational Electromagnetism and Acoustics", Oberwolfach, Allemagne, Février 2010.
  - Invitation to give a course at “OSRCs: Theory, numerics and applications" at the ETH Zurich, mai 2010.
  - 10$^{\text{ièmes}}$ Journées de "Calcul Scientifique et Modélisation Mathématique", LAMFA, Amiens, June 2010.
  - Conference “Frontiers in Applied and Computational Mathematics", New Jersey Institute of Technology, USA, Mai, 2010.
- Henrot
  - International Conference on Isoperimetric Problems, (Mai 2010, Carthage, Tunisie).
  - Workshop on“Analytical and computational methods in geometric optimization problems" (July 2010, Frankfurt (Allemagne)).
- Chambrion
  - Workshop “Partial Differential Equation” (June 2010, Besançon).
  - Workshop “Quantum Control” at IHP (December 2010, Paris).
- Munnier
  - “International Workshop in Fluid-Structure Interaction Problems”, Foz do Arelho (Portugal), September 6-8, 2010.
  - Workshop "Self-propelled motions in fluids : modeling, analysis and control" in Nancy, France, October 21-22 2010.
- Ramdani
  - Workshop “Problèmes Inverses” de la Fédération Charles Hermite (IECN, March 2010).
  - Workshop “Inverse Problems for Waves: Methods and Applications”, http://www.cmap.polytechnique.fr/~defi/mmsn2010/welcome.html (École Polytechnique, March 2010).
- Sigalotti
  - Workshop “Hyperbolic Systems and Control in Networks", Institut Henri Poincaré, (October 2010).
  - “Franco-Brazilian Workshop on Sub-Riemannian Geometry", Federal University of Pará, Belém, Brésil, (August 2010).
  - “Premières Journées scientifiques du LEM2I", Tipaza, Algérie, (June 2010).
  - Workshop “New Trends in Sub-Riemanian Geometry", Nice, (March 2010).
- Takahashi
  - WIPA2010 Workshop on Inverse Problems and Applications, January 18-22, 2010, Valparaíso, Chile.
  - 8th AIMS Conference on Dynamical Systems, Differential Equations and Applications AIMS 2010, May 25–28, 2010, Dresden, Germany.

- Tucsnak
  - *Workshop on Mathematical challenges in hidroelasticity*, Edinburgh, 2010.
  - *Workshop on Penalization methods in fluid mechanics*, Luminy, 2010.
  - *Workshop on Fictitious domain methods in fluid mechanics*, Maratea (Italy), 2010.
  - Main lecturer at *Control of parabolic Partial Differential Equations*, Paris, 2010.
- Valein
  - Workshop on Control and Inverse Problems, (June 2010, Besançon, France).
- Vivalda
  - “Colloque de la SMT" March 15-18, 2010.

### 8.1.3. Invitations

- Alabau
  - Invitation at Mexico University (UNAM, Mexico), June 2010.
  - One month invitation at the Bilbao Center for Applied Mathematics (BCAM) by Enrique Zuazua, Bilbao, Spain (April-May 2010).
  - Invitation at the University of the Frontera (Temuco, Chile, March 2010).
- Antoine
  - One week invitation at the ETH Zurich, May 2010.
- Chambrion
  - Invited for one week in April 2010 in the Pacific Institute for Mathematical Sciences (Vancouver).
  - Invited in Erlangen for one week in December 2010.
- Scheid, Munnier
  - Two weeks invitation at the CMM (Center for Mathematical Modeling), January 2010.
- Takahashi
  - Invitation at the University of Santiago (Chile).
- Tucsnak
  - Basque Center for Applied Mathemathics, Bilbao, Spain.
- Valein

  One week invitation at LAAS (Toulouse) in the MAC team, may 2010.

### 8.1.4. Seminars

- Antoine
  - Seminar of Applied Mathematics (SAM), ETH Zurich, May 2010.
  - Seminar of the Laboratoire A. Dieudonné, Université de Nice Sophia Antipolis, June 2010.
- Munnier
  - PDEs seminar at the university of Grenoble.
  - UBC, post-docs colloquium, Vancouver.
- Valein

- Seminar at LAAS in Toulouse, May 2010.
- Seminar at INRIA Rocquencourt in SISYPHE team, June 2010.
- Seminar “Analyse, Optimisation, Contrôle" of the Fédération Charles Hermite, Nancy, June 2010.
- Seminar “EDP of GDR MACS", Nancy, September 2010.

### *8.1.5. Participation to conferences*

- Munnier
  - ACC 2010 (American Control Conference), IEEE, Baltimore.
- Ramdani
  - “Etude numérique de la résolution par équations intégrales de la diffraction multiple par des disques", 10ème Congrès Français d'Acoustique (CFA'10), Lyon, Avril 2010.
- Valein
  - Workshop on Analysis and Numerics of PDE Constrained Optimization with presentation, Lambrecht (Germany), July 2010.
  - Workshop of GDRE CONEDP, CIRM, Luminy, January 2010.
  - Control of Partial and Differential Equations and Applications Trimester, IHP, Paris, October-November 2010.
- Vivalda
  - Participation to Nolcos 2010, 1-3 September 2010. *On a Class of Switched Linear Systems*.

### *8.1.6. Editorial activities and scientific committee's memberships*

- Antoine
  - Member of the scientific comity in the “Seventh International Conference on Engineering Computational Technology", Valencia, Spain, 14-17 September 2010.
  - Member of the scientific comity in the conference “Waves 2011, The 10th International Conference on Mathematical and Numerical Aspects of Waves", Vancouver, Canada, July 2011.
- Tucsnak
  - Associated editor of “SIAM Journal on Control” and of “ESAIM COCV”.

## 8.2. Teaching activities

Most of the project members are professors or assistant professors so they have an important teaching activity. We mention here only the graduate courses.

- Non linear analysis of PDE's and applications (Alabau);
- Scientific Computing (Henrot);
- Integral equations (Pinçon and Ramdani);
- Semigroups and evolution equations in Hilbert spaces (Tucsnak).

# 9. Bibliography

## Major publications by the team in recent years

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## Publications of the year

### Doctoral Dissertations and Habilitation Theses

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[12] I. ELLOUZE. *Etude de la stabilité et stabilisation des systèmes à retard et des systèmes impulsifs*, Université de Metz et Faculté des sciences de Sfax, 2010.

[13] P. KLEIN. *Construction et Analyse de conditions aux limites artificielles pour des équations de Schrödinger avec potentiels et non linéarités*, Nancy Université, 2010.

[14] M. SIGALOTTI. *Contrôle de systèmes mécaniques et quantiques par des méthodes géométriques*, Nancy Université, 2010, Habilitation à Diriger des Recherches.

### Articles in International Peer-Reviewed Journal

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