IN PARTNERSHIP WITH:
CNRS

Université de Lorraine

Activity Report 2011

Project-Team CORIDA

Robust control of infinite dimensional systems and applications

IN COLLABORATION WITH: Institut Elie Cartan Nancy (IECN), Laboratoire de mathématiques et applications de Metz (LMAM)

RESEARCH CENTER
Nancy - Grand Est

THEME
Modeling, Optimization, and Control of Dynamic Systems

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Project-Team CORIDA

Keywords: System Analysis And Control, Robust Control, Fluid Dynamics, Vibrations

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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 [82]), multiplier methods (cf. Lions [78]) or micro-local analysis techniques (cf. Bardos–Lebeau–Rauch [71]). 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

Karim Ramdani has been promoted to Senior Researcher ("Directeur de recherche") in October 2011.

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 [75] and the references therein). The feedback control of fluid motion has also been recently investigated by several research teams (see, for instance Barbu [70] 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.

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

Participants: Xavier Antoine, 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 [79]. 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 [80]. Using the result of Miller, K. Ramdani, T. Takahashi, M. Tucsnak have obtained in [5] a new spectral formulation of the criterion of Liu [79], 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^∞ 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^∞ 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 [77] , 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 [83]. In the case of systems governed by linear PDE's some similar estimates have been obtained only very recently (see, for instance Miller [80]). 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 [69]).

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 [84], 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. [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/ .

5. Software

5.1. Simulation of viscous fluid-structure interactions

Participants: Takéo Takahashi [correspondant], Jean-François Scheid, Jérôme Lohéac.

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. In order to solve the 3D Navier-Stokes equations which model the viscous fluid, we have implemented an efficient 3D Stokes sparse solver for MATLAB and a 3D characteristics method to deal with the nonlinearity of Navier-Stokes equations. This year, we have also started to unify our 2D fluid-structure codes (fluid alone, fluid with rigid bodies and fluid with fishes).

Another code has been developed in the case of self-propelled deformable object moving into viscous fluid. Our aim is to build a deformable ball which could swim in a viscous fluid. In order to do this we have started a collaboration with a team from the CRAN (Research Centre for Automatic Control). This software solves numerically 3D Stokes equations using finite elements methods. The source code is written for use with MATLAB thanks to a C++ library developped by ALICE.

- Version: v0.5
- Programming language: MATLABc++

6. New Results

6.1. 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.

6.1.1. Incompressible viscous fluids

- In [31], García and Takahashi present some abstract results giving a general connection between null-controllability and several inverse problems for a class of parabolic equations. They obtain some conditional stability estimates for the inverse problems consisting of determining the initial condition and the source term, from interior or boundary measurements. They apply this framework for Stokes system with interior and boundary observations, for a coupling of two Stokes system and a linear fluid-structure system.
- Nečasová, Takahashi and Tucsnak consider in [43] the three-dimensional motion of a self-propelled deformable structure into a viscous incompressible fluid. The deformation of the solid is given whereas its position is unknown. Such a system could model the propulsion of fish-like swimmers. The equations of motion of the fluid are the Navier-Stokes equations and the equations for the structure are deduced from Newton's laws. The corresponding system is a free-boundary problem and the main result they obtain is the existence of weak solutions for this problem.
- In [29] we give a controllability result for a simplified 1D fluid-structure system.
- In [39] we give a detailed analysis of a phase field type model describing the motions of vesicles in a viscous incompressible fluid.
- In [40] we study a controllability problem for a simplified one dimensional model for the motion of a rigid body in a viscous fluid. One of the novelties brought in with respect to the existing literature consist in the fact that we use a single scalar control. Moreover, we introduce a new methodology, which can be used for other nonlinear parabolic systems, independently of the techniques previously used for the linearized problem. This methodology is based on an abstract argument for the null controllability of parabolic equations in the presence of source terms and it avoids tackling linearized problems with time dependent coefficients.

6.1.2. Ideal fluids

- In [42], the author studies the motion of an hyperelastic body immersed in a perfect fluid. The recourse to a strain energy density function in the modeling allows many different constitutive equations for the hyperelastic material to be considered. Numerical simulation are performed, aiming to study passive locomotion (i.e. locomotion at zero energy cost).
- In [27], we study the approximate controllability of 2D swimmer in an ideal fluid. The result includes an approximate tracking result of both the shape and the position of the swimmer.

6.2. Frequency tools for the analysis of PDE's

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

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

- In [21] we propose some strategies to solve numerically the difficult problem of multiple scattering by a large number of disks at high frequency. To achieve this, we combine a Fourier series decomposition with the EFIE integral equation. Numerical examples will be presented to show the efficiency of our method.
- In [20], we propose to simulate complex nonlinear physics problems related to the Schrödinger equations by using relaxation techniques coupled with absorbing boundary conditions or PMLs. This shows that these two methods are much more accurate than the usual complex scaling/absorbing potential approaches widely used in physics for domain truncation.
- In [19], complete high order absorbing boundary conditions are proposed, discretize and simulate for one- and two-dimensional nonlinear Schrödinger equations. In [38], we propose new accurate absorbing boundary condition for computing nonlinear eigenvalue problems related to the Schrödinger equation.
- In [57], we propose a review of how pseudo differential operators theory help in building analytical preconditioners and well-posed integral equations for acoustics scattering. In [26], we propose a new efficient and robust domain decomposition method for solving large scale three-dimensional acoustic scattering problems.

6.3. 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, Roberto Guglielmi.

6.3.1. Observability

- The PhD of Ghislain HAINE is devoted to the analysis of observers based techniques for solving inverse problems. In [34], we provide a convergence analysis of the iterative reconstruction algorithm proposed by Ramdani *et al.* in [81]. More precisely, we propose a complete numerical analysis for semi-discrete (in space) and fully discrete approximations of the iterative algorithm using finite elements in space and an implicit Euler method in time. In order to disseminate our reconstruction method in the community of Automatic and control engineering, we wrote an engineer's oriented note [33] presenting the main ideas of our algorithm.

6.3.2. Control

- In [48], we develop a model that describes the impact of the amount of soot in the filter on the Diesel engine performance. This model is used to determine the optimal amount of soot on which the regeneration of the particulate filter shall start.
- In [49], we give sufficient conditions for the simultaneous approximate controllability of a bilinear Schrödinger equation driven by a single scalar control in the case where every energy level is non-degenerate and the control potential couples each pair of energy levels.
- In [25], we give sufficient conditions for the simultaneous approximate controllability of a bilinear Schrödinger equation driven by a single scalar control under a generic condition of coupling of all energy levels via a chain of non-degenerate transitions. The result applies for systems with degenerate energy levels or when the coupling operator does not couple directly each pair of energy levels.
- In [16] we prove exact controllability for symmetric coupled wave equations by a single control in the case of coupling and control regions which do not intersect. For this, we use and extend the two-level energy method introduced by Alabau-Boussouira (2001, 2003). Using transmutation, we derive null controllability results for coupled parabolic and Schrödinger equations. This is the first

positive quantitative result, in a multi-dimensional framework with control and coupling regions with empty intersection. Such questions have been considered using Carleman estimates but no positive quantitative results could be derived in the case of control and coupling regions which do not intersect.

- In [30] we propose a new method for the approximation of exact controls of a second order infinite dimensional system with bounded input operator. The algorithm combines Russell's "stabilizability implies controllability" principle with the Galerkin method. The main new feature of this work consists of giving precise error estimates.

6.3.3. Stabilization

- In [44] 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 [52] 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. In particular, we present the optimal-weight convexity method (Alabau-Boussouira 2005, 2010) in both the finite dimensional and infinite dimensional framework and give applications to semi-discretization of hyperbolic PDE's.
- In [14], we consider stabilization of coupled systems of hyperbolic PDE's with hybrid boundary conditions, by a reduced number of closed loop globally distributed controls. We establish polynomial stabilization for such systems under a new compatibility condition. We also derive decay rates for explicit initial data using interpolation theory.
- In [15], we consider stabilization of coupled systems of wave-type, with localized couplings and either localized internal closed loop controls or boundary control. We establish polynomial decay rates for coupling and damping regions which do not intersect in the one-dimensional case. We also derive results in the multi-dimensional case, under multiplier type conditions for both the coupling and damping regions. The novelty and difficulty is to consider localized couplings.
- In [13] we give a constructive proof of Gibson's stability theorem, some extension and further positive and negative applications of this result.
- Very few lower energy estimates are available in the literature. The main one has been proved in the one-dimensional case for a locally distributed power-like damping for the wave equation in 1995 by Haraux. This approach does not generalize to multi-dimensional cases and for systems of equations. In [11], we prove strong energy and weak velocity lower estimates for the nonlinearly damped Timoshenko beams (coupled system), and for Petrowsky equations in two space dimensions.
- In [12], 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). The approach is based on the optimal-weight convexity method (Alabau-Boussouira 2005, 2010). Our results generalize previous results by Haraux (1989) and Ammari and Tucsnak (2001) for linear feedbacks.
- In [17], we study the stabilization of Bresse system, which models vibrations of a beam through three coupled wave equations. We establish polynomial stabilization of the full system by a single feedback control.
- In [23], Badra (University of Pau) and Takahashi consider the stabilization of the system $y' = Ay + Bu$ where $A : \mathcal{D}(A) \to \mathcal{X}$ be the generator of an analytic semigroup and $B : \mathcal{U} \to [\mathcal{D}(A^*)]'$ a quasi-bounded operator. They consider controls u which are the 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.

- In [32] we tackle an unsolved difficulty in the control of vibrating systems, consisting in the fact that a small delay in the application of a feedback control may destroy the stabilizing effect of the control. We consider a vibrating string that is fixed at one end and stabilized with a boundary feedback with delay at the other end and we show that certain delays (large, in general) in the boundary feedback preserve the exponential stability of the system.
- In [18] we consider N Euler-Bernoulli beams and N strings alternatively connected to one another and forming a chain beginning with a string. We study the strong and polynomial stabilities of this system on this network and the spectrum of the corresponding conservative system.
- In [45] we study the asymptotic behavior of the solution of the non-homogeneous elastic systems with voids and a thermal effect. Our main results concern strong and polynomial stabilities (since this system suffers of exponential stability).
- In [24] we are interested in an inverse problem for the wave equation with potential on a star-shaped network. We prove the Lipschitz stability of the inverse problem consisting in the determination of the potential on each string of the network with Neumann boundary measurements at all but one external vertices. Our main tool, proved in this article, is a global Carleman estimate.
- In [35] we consider switched systems on Banach and Hilbert spaces governed by strongly continuous one-parameter semigroups of linear evolution operators. We provide necessary and sufficient conditions for their global exponential stability, uniform with respect to the switching signal, in terms of the existence of a Lyapunov function common to all modes.
- In [47], 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.

6.3.4. Other problems

- In [37], we study a spectral problem related to a reaction-diffusion model where the preys and the predators do not live on the same area. We are interested in the optimal zone where the control should take place. First we prove existence of an optimal domain in a natural class. Then, it seems plausible that the optimal domain is localized in the intersection of the living areas of the two species. We prove this fact in one dimension for small size of domains.
- In [41], we explain why Donnelly's proof of the gap conjecture is not correct.
- In [22], we study the set of points, in the plane, defined by $\{(x, y) = (\lambda_1(\Omega), \lambda_2(\Omega)),\ |\Omega| = 1\}$, where $(\lambda_1(\Omega), \lambda_2(\Omega))$ are either the two first eigenvalues of the Dirichlet-Laplacian, or the two first non trivial eigenvalues of the Neumann-Laplacian. We consider the case of general open sets together with the case of convex open domains. We give some qualitative properties of these sets, show some pictures obtained through numerical computations and state several open problems.
- In [28], we look for the minimizers of the functional $J_\lambda(\Omega) = \lambda|\Omega| - P(\Omega)$ among planar convex domains constrained to lie into a given ring. We prove that, according to the values of the parameter λ, the solutions are either a disc or a polygon. In this last case, we describe completely the polygonal solutions by reducing the problem to a finite dimensional optimization problem. We recover classical inequalities for convex sets involving area, perimeter and inradius or circumradius and find a new one.

7. Contracts and Grants with Industry

7.1. ANR

We continued in 2011 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;

7.2. 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) and ONERA Toulouse (4 participants).

7.3. 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.

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. Collaboration with Université de Franche Comté

In September 2010, we began a cooperation with Université de Franche-Comté within a COLOR project funded for one year by INRIA-Nancy Grand Est. The main objective of the cooperation is the control of the bilinear Schrödinger equation with unbounded control potentials. The first results have been submitted to international journals [63], [62] or international conferences [60], [61] and are currently under review.

8.2. National Initiatives

8.2.1. 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.

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

  - 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.

8.2.2. 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”.

8.3. 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*.

8.4. International Initiatives

8.4.1. Projects

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

8.4.2. 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).

8.4.3. Visits of Foreign researchers

Evans Harrell (Georgia Tech, Atlanta), Gérard Philippin (U. Laval, Québec), Paolo Salani (U. Florence).

9. Dissemination

9.1. Animation of the scientific community

9.1.1. Organization of conferences

- The workshop ”The Stochastic Schrödinger Equations in Selected Physics Problems”, CEA, Espace de Structure Nucléaire Théorique, Saclay, was partially organized by X. Antoine, December 2011.
- The conference “Contrôle et énergie” has been organized in Nancy by T. Chambrion and G. Millerioux (CRAN, Nancy).

9.1.2. Editorial activities

- F. Alabau is a member of the editorial board of the journal Evolution Equations and Control Theory (EECT), American Institute of Mathematics and Sciences (AIMS)

9.1.3. Expertise

- F. Alabau is a member of the evaluation panel for the INDAM post- doctoral fellowship, $7th$ european program and member of the scientific committee of the CIMPA-UNESCO-TUNISIE "Contrôle et stabilisation des EDP", 9-19 may, Monastir, Tunisia. In may 2011, she carried out an expertise for Paris town for the program "Research in Paris", for foreign researchers. In February 2011, she carried out an expertise for promotion to the highest grade of professorship for a Research Institute in mathematics, India.

9.1.4. Invited conferences (selection)

- K. Ramdani was invited to
  - Workshop “Control of PDE and Inverse Problems” (Amiens, September 2011);
  - Workshop “Polaritons 2011” (CIRM, April 2011).
- F. Alabau took part to conferences
  - GDRE CONEDP, LATP, Marseille, 21-23 november 2011;
  - IFIP TC7 2011, Mini-symposium Analysis and control of composite PDE systems: new challenges and methods, 12-16 September 2011, Berlin;
  - Conference “Partial Differential Equations, Optimal Design and Numerics”, IV Edition, International Center of Sciences, Benasque, Espagne (Plenary conference);
  - Conference “Partial Differential Equations, Optimal Design and Numerics”, IV Edition, International Center of Sciences, Benasque, Espagne. Presentation of the GDRE CONEDP;
  - Workshop program of INDAM, GDRE CONEDP, “New trends in Analysis and Control of Nonlinear PDEs”, 13-15 june 2011, Rome (Plenary conference);
  - Conference on Modeling and Control of Nonlinear Evolution Equations, Trieste, 24-27 may 2011, Italy. (plenary conference).
- T. Takahashi was invited to
  - Control of Partial and Differential Equations Days in Orleans, September 26-27, 2011;
  - International Workshop on Control and Optimization of PDEs, Graz (Austria), October 10-14, 2011
- T. Chambrion was invited to

  - Workshop on Quantum Control, April 2011, Banff, Canada.
- J.F. Scheid was invited to
  - Seminar at the Applied Mathematics Laboratory (LJK) of the University of Grenoble, January 2011;
  - Seminar "GDR MACS / GDR "Contrôle des décollements", ENS Cachan, november 2011.
- X. Antoine was invited to
  - General meeting of GDR Ondes, Nice, 24-26 octobre 2011;
  - Seminar in Zurich University, Switzerland, March 2011;
  - Seminar of nuclear physics in CEA Bruyères-le-Châtel, June 2011;
  - Seminar in Genève University, Switzerland, October 2011.
  - Université de Liège, Belgique, one month stay, November-December 2011.

9.2. Teaching

9.2.1. Teaching positions

Most of the members of the team have a teaching position (192 hours a year) in one of the universities of Lorraine.

- Fatiha Alabau has a full time full professor position in the University of Metz;
- Xavier Antoine has a full time full professor position at INPL;
- Thomas Chambrion has a full time associate professor position at ESSTIN;
- Antoine Henrot has a full time full professor position at INPL;
- Bruno Pinçon has a full time associate professor position at ESIAL;
- Lionel Rosier has a full time full professor position at ESSTIN;
- Jean-François Scheid has a full time associate professor position at ESIAL;
- Marius Tucsnak has a full time full professor position at UHP;
- Julie Valein has a full time associate professor position at ESSTIN.

9.2.2. Other teaching activities

- F. Alabau gave a course on control and stabilization of PDE's, USTBH, Algiers, Algeria (graduate level);
- F. Alabau gave a course on "Stabilization and observability of ordinary and partial differential equations" CIMPA-UNESCO-TUNISIE school on "Contrôle et stabilisation des équations aux dérivées partielles, 9-19 may, Monastir, Tunisia (graduate level);
- T. Chambrion gave a lecture on "Control of bilinear Schrödinger equations" in Würzburg, Germany (graduate level);

9.2.3. PhD & HdR

- Bertrand Thierry has defended his thesis "Analyse et Simulations Numériques du Retournement Temporel et de la Diffraction Multiple" (supervisor:X. Antoine and K. Ramdani);
- Erica Schwindt defended her PhD thesis "Problèmes d'interaction entre un fluide newtonien incompressible et une structure" in cotutelle between the University of Chile and the University of Nancy 1 with Carlos Conca and Takéo Takahashi. Her work deals with two different fluid–structure interaction problems in the three dimensional case: in the first problem, she make a theoretical analysis of a problem of interaction between a deformable structure and an incompressible Newtonian fluid; in the second problem, she consider a geometrical inverse problem associated to a fluid-rigid body system.

- Jérôme Loheac is a PhD student in UHP since 2010 (supervisor: M. Tucsnak);
- Roberto Guglielmi is a PhD student in cotutelle with University Tor Vergata, Roma, Italy, since october 2010 (co-supervisor F. Alabau).

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