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Project-Team CORIDA

Robust Control Of Infinite Dimensional Systems and Applications

Nancy - Grand Est

Theme : Modeling, Optimization, and Control of Dynamic Systems

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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.

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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 [70]), multiplier methods (cf. Lions [65]) or micro-local analysis techniques (cf. Bardos–Lebeau–Rauch [57]). 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

A remarkable fact in 2009 was that all ANR projects submitted have been accepted. More than 400000 euros of funding have been obtained in this way for the next four years. Moreover, CORIDA has been successfully evaluated in March 2009 and the Evaluation Committee proposed the renewal for four years of the project.

3. Scientific Foundations

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

Participants: Thomas Chambrion, Antoine Henrot, Jean Houot, 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 [62] and the references therein). The feedback control of fluid motion has also been recently investigated by several research teams (see, for instance Barbu [56] 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 [7]). Another important result gives the existence and the uniqueness of strong solutions for two or three-dimensional Navier–Stokes fluid (see [8]). 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^∞ 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 [58]. 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 [71]). An important advance in the study of this problem has been achieved in the work of Rosier [69] 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 [66]. This characterization can be related to the Hautus criterion in the theory of finite dimensional systems (cf. [61]). 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 [67]. Using the result of Miller, K. Ramdani, T. Takahashi, M. Tucsnak have obtained in [5] a new spectral formulation of the criterion of Liu [66], 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 [59] 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 [60]. 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 [64] , 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 [73]. In the case of systems governed by linear PDE's some similar estimates have been obtained only very recently (see, for instance Miller [67]). 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 [54]).

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 [74], 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. [75]. 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. [63], 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.

4.2.2. Biology

The observation of nature and of the "perfection" of most of its mechanisms of living beings drives us to search **a principle of optimality** which governs those mechanisms. If a mathematical model exists for describing a biological phenomenon or component of a living being, there is a temptation to quantify the optimality by finding a functional which leads to the optimality principle. The confrontation between the computed optimum and the real one leads us to validate or invalidate the model and/or the choice of the functional. This inverse modeling method consists in finding the mathematical model starting from observations and theirs consequences. If the optimal shape which is issued from the mathematical model is close to the real shape, we have reasons to believe that the full model (equation and functional) is good. If not, one has to reject it and find another one, or improve it.

The mathematical study of these questions strongly uses tools of "shape variation and optimization" as developed in the book [3].

5. Software

5.1. SCISPT Scilab toolbox

Participant: Bruno Pinçon [correspondant].

Our aim is to develop Scilab tools for the numerical approximation of PDE's. This task requires powerful sparse matrix primitives, which are not currently available in Scilab. We have thus developed the SCISPT Scilab toolbox, which interfaces the sparse solvers UMFPACK of Tim Davis and TAUCS SNMF of Sivan Toledo. It also provides various utilities to deal with sparse matrices (estimate of the condition number, sparse pattern visualization, etc.). This module has been recently integrated in SCILAB-5.

5.2. 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 already developed by the team. These codes are 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. A 3D Stokes sparse solver for MATLAB is now available. Since we want to have an accurate solver, we use high order finite elements method. As a result, the size of the linear systems to be solved is very huge, requiring very large CPU time resources and large memory storage. In 3D simulations, only iterative solvers are thinkable. This also requires the use of efficient preconditioners for the Stokes equations in order to reduce the number of iteration. Several preconditioners have been implemented and tested. These developments are still in progress.

5.3. 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) gathers 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/ .

A number of numerical codes for the simulation for fluids and fluid-structure problems has been already developped by the team. These codes are 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. A 3D Stokes sparse solver for MATLAB is now available. Since we want to have an accurate solver, we use high order finite elements method. As a result, the size of the linear systems to be solved is very huge, requiring very large CPU time ressources and large memory storage. In 3D simulations, only iterative solvers are thinkable. This also requieres the use of efficient preconditioners for Stokes equations in order to reduce the number of iteration. Several preconditioners have been implemented and tested. These developments are still in progress.

6. New Results

6.1. Analysis and control of fluids and of fluid-structure interactions

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

The study of the a fluid-structure systems depends a lot of the nature of the fluid considered and in particular on the Reynolds number. We have split the new results obtained in 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 which 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 interested to understand self-propelled motions which is one the main goal of our work. In the last part, we have finally given some numerical results.

It is worth noting that an important part of this work is done in collaboration with a group from the University of Chile through the associated team ANCIF. The Chilean members of our associated team are Jorge San Martín, Jaime Ortega, Carlos Conca, Patricio Cumsille and Axel Osses.

6.1.1. *Incompressible viscous fluids*

Concerning the system composed by a rigid ball moving into a viscous incompressible fluid, there are still many open questions concerning the existence or not of shocks or contacts between rigid bodies. It was proved recently 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 [27], Hillairet (University of Toulouse) and Takahashi consider a similar geometry of a ball falling over an horizontal plane, but in 3D. They show that for any weak solution of the corresponding system satisfying the energy inequality, the rigid ball never touches the plane in finite time. Then, using some symmetry result, and considering again some particular geometry, Hillairet (University of Toulouse) and Takahashi prove in [26] that in 3D, there exists contact in finite time. It implies a blow-up of the strong solutions at the time of the contact.

We continued the work initiated in [72] on the control theoretic interpretation of the motion of aquatic organisms. More precisely, in Sigalotti and Vivalda [40] we consider a finite-dimensional model for the motion of *ciliata*, coupling Newton's laws for the organism with 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.

Another type of control problem was tackled for a simplified model by Tucsnak and Vanninathan (Bangalore, India). In [42] we consider the equations modeling the coupled vibrations of a fluid-solid system. The control acts in a subset of a domain occupied by the fluid. Our main result asserts that we have exact controllability and exponential stabilizability provided that the support of the control contains a neighborhood of the solid and a neighborhood of the exterior boundary.

6.1.2. Inviscid fluids

In [33] we investigate the motion of a rigid ball surrounded by an incompressible perfect fluid occupying $\mathbb{R}^N$. We prove the existence, uniqueness, and persistence of the regularity for the solutions of this fluide-structure interaction problem.

The article [31] is concerned with comparing Newtonian and Lagrangian methodsin Mechanics to determine theEuler-Lagrange equations governing a collection of shape-changing bodies immersed in a perfect fluid. We prove that under smoothness assumptions on the fluid-bodiesinterface, Newtonian and Lagrangian formalisms yield the same equations ofmotion.

6.1.3. Numerical Analysis and Numerical Simulations

In [39] Takahashi, in collaboration with San Martín and Smaranda (University of Chile), analyzes a finite element method for a Stokes problem with moving domain. The numerical scheme uses the classical Arbitrary Lagrangian Eulerian formulation which allows to deform the mesh in order to follow the motion of the spatial domain. The results proved in this article state the convergence of the solutions of the semi-discretized (with respect to the space variable) and of the fully-discrete problems towards the solutions of the Stokes system. ‘

6.1.4. Related problems

In [24], 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.

6.2. Frequency tools for the analysis of PDE's

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

6.2.1. Observation and Control for operator semigroups

The main topics covered in the monograph [53] are the study of the observation and control operators for systems which can be described by operator semigroups in Hilbert spaces, with emphasis on observability and on controllability properties. The abstract results are supported by a large number of examples coming from partial differential equations. These examples are worked out in detail and they cover to a large extent systems governed by the classical linear partial differential equations. This work is meant to be an elementary introduction in this theory. The first meaning of “elementary” is that the text is aimed to be accessible to any reader familiar with linear algebra, calculus and which has some basic knowledge on Hilbert spaces and on differential equations. We introduce everything needed on operator semigroups and most of the used background is summarized in the Appendices, often with proofs. The second meaning of “elementary” is that we only cover results for which we can provide complete proofs.

6.2.2. Optics

In [17], we present a systematic method to derive Beam Propagation Models for optical waveguides. The technique is based on the use of the symbolic calculus rules for pseudodifferential operators. The cases of straight and bent optical waveguides are successively considered.

6.2.3. Numerical methods for high-frequency scattering problems

In [51], we propose a review of recent numerical methods for solving high-frequency multiple scattering problems. We review recent developments for three main families of approaches: Fourier series based methods, PDE's approaches and Integral Equations based techniques.

For two- and three-dimensional acoustics high-frequency scattering problems, a new method is proposed in [18]. Finally, in [29], the authors prospects the numerical difficulties related to the plane wave finite element method for high-frequency problems.

6.3. Observability, controllability and stabilization in the time domain

Participants: Fatiha Alabau, Xavier Antoine, Thomas Chambrion, Nicolae Cindea, Antoine Henrot, Karim Ramdani, Lionel Rosier, Mario Sigalotti, Takéo Takahashi, Marius Tucsnak, Jean-Claude Vivalda.

6.3.1. Control

In the review paper [50], appeared in the Springer Encyclopedia of Complexity and Systems Science, we present an overview of recent results on Control Theory for nonlinear PDE's of parabolic as well as hyperbolic type. We address mainly the topics of controllability, stabilization and optimal control. We also indicate future directions of research.

In [38] we investigate the null controllability of the complex Ginzburg-Landau equation which may serve as a simplified model of turbulence. We derive a new Carleman estimate and prove that a local null controllability holds.

In [34] we give an overall review of the results obtained so far in the control and stabilization of the Korteweg-de Vries equation.

In [41] we study the exact observability of systems governed by the Schrödinger equation in a rectangle with homogeneous Dirichlet (respectively Neumann) boundary conditions and with Neumann (respectively Dirichlet) boundary observation. Generalizing results by Ramdani, Takahashi, Tenenbaum and Tucsnak [68], we prove that these systems are exactly observable in *in arbitrarily small time*. Moreover, we show that the above results hold even if the observation regions have *arbitrarily small measures*.

In [13], Takahashi and Tucsnak, in collaboration with Alves and Silvestre (IST, Lisbon), consider a general link between the problem of controllability and the problem of inverse source problems. More precisely, they provide a general framework in which if a system is exactly controllable, then a source term in this system can be identified by knowing its intensity and appropriate observations which often correspond to measurements of some boundary traces. This abstract theory is then applied to obtain new identifiability results for a system governed by the Euler-Bernoulli plate equation.

In [23], Cindea and Tucsnak study the internal exact controllability of a semilinear system modeling plate vibrations, known as Berger's equation. The main result asserts that the system is locally exactly controllable if the Euler-Bernoulli equation, with the same control operator, forms an exactly controllable system.

In [45] and [47], we provide sufficient conditions for simultaneous tracking of bilinear Schrödinger equations. In [49], the results of [47] are proven to apply to a generic bilinear Schrödinger equation. In [46], the results of [47] are applied to get the first (to our knowledge) example of positive control result of bilinear Schrödinger equations on a non-simply-connected manifold.

In [32] we study the genericity of some conditions issuing from the problem of controlling the bilinear Schrëdinger equation. In particular, we prove that the squared eigenfunctions of the Dirichlet-Laplace operator are linearly independent generically with respect to the domain.

In the invited paper [16], pseudodifferential and paradifferential operator techniques for approximating absorbing boundary conditions for nonlinear wave and Schrödinger equations are reviewed. In [15], we propose new absorbing boundary conditions and associated stable approximation schemes for Schrödinger equations with general variable potentials.

In [37], we investigate the exact controllability and stabilization of the cubic Schrödinger equation posed on a bounded interval. Using Bourgain analysis, we obtain local results in the natural space $L^2(I)$. These results are next extended to arbitrary products of intervals in [35]. Both the internal control and the boundary control are considered, and exact control results with small control regions are derived in any dimension $N \geq 2$. Finally, in [36] we investigate the boundary control of the semilinear Schrödinger equation posed on arbitrary bounded domains $\Omega \subset \mathbb{R}^N$.

6.3.2. Stabilization

In [28], we propose 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) observation on a finite time interval. Our method uses stabilization techniques to construct time-reversed observers in order to estimate the initial state.

In [52] we use the results from [41] in order to obtain decay rates for the semigroups obtained in the feedback boundary control of the Euler-Bernoulli plate equation.

In [30] the authors study the internal controllability and stabilizability of a family of Boussinesq systems recently proposed by J. L. Bona, M. Chen and J.-C. Saut to describe the two-way propagation of small amplitude gravity waves on the surface of water in a canal.

In collaboration with P. Cannarsa, we give in [11] optimal energy decay rates for memory-dissipative hyperbolic PDE's with general form of decay of the kernel. We give various examples of applications for kernels which decay faster or slower than polynomially.

In [12], we consider the case of a wave equation subjected to a memory-damping on the boundary. Here the kernel is assumed to be singular at initial time. Such kernels model more sharply visco-elastic materials. We establish polynomial energy decay rates for sufficiently smooth solutions.

6.3.3. Finite dimensional systems

In [14], we deal with the problem of global output stabilization for a class of Euler-Lagrange systems, the unmeasured part of the state being the velocity. The output feedback relies on a transformation which allows us to write the system under a triangular form.

In [40], we consider a finite dimensional model for the motion of a micro-organism which writes

$$\begin{aligned} \dot{z} &= Az + E(z) + Bu \\ \dot{\zeta} &= R\xi \\ \dot{R} &= RS(\omega) \end{aligned}$$

the control u represents the action of a layer of *cilia* which covers the surface of the micro-organism and $E(z)$ is a nonlinear term. We proved that this system is generically controllable if the dimension of the space of controls is at least 3.

In the framework of the CPER AOC SC2, we have studied the problem of the synthesis of an observer for the multicell converter. The dynamics of this device can be modeled by a switched linear system which writes

$$\dot{x} = \sum_{i=1}^{N} \alpha_i(t) A_i x(t)$$

with $\alpha_i(t) \in \{0,1\}$ and $\sum_{i=1}^{N} \alpha_i(t) = 1$.

In a submitted paper by P. Riedinger, U. Serres and J.-C. Vivalda, we investigate the asymptotic stability at the origin for switched linear systems satisfying the following property: there exist a positive definite matrix P such that $A_i^T P + PA_i = -Q_i$ with Q_i semi-definite positive. We introduce several notions of dwell-time and we prove the convergence to 0 of the state of the system if some of these conditions of dwell-time are satisfied. When the state of the system does not tend to the origin, we describe the ω-limit set. This work has been the subject of an article (submitted).

In [10] and [43] we consider a generalization of Riemannian geometry which naturally arises in optimal control theory and in the study of hypoelliptic operators. We obtain in this framework a generalization of the Gauss-Bonnet formula.

In [44] we consider the magnetization switching in small ferromagnetic particles. We give necessary and sufficient conditions for controllability with an horizontal magnetic field or a current polarized in spin.

In [48] we prove the stabilizability of a class of switched systems for which the linear dynamics corresponding to some parameters are unstable (but whose eigenvalues have nonpositive real part), under an hypothesis of persistent excitation. We show that the maximal rate of decay that can be obtained exhibits a bifurcation behavior.

6.4. Biology and Medicine

Participants: Nicolae Cîndea, Antoine Henrot, Marius Tucsnak.

6.4.1. Medicine

A quite recent activity of our group consists in proposing new methods for the reconstruction of moving objects via Magnetic Resonance Imaging (MRI). This is the main topic of the Phd thesis of Cîndea, which is directed jointly by Tucsnak and Vuissoz from the MRI laboratory of the University Hospital of Nancy. One of the ideas of this work is to use the theory of observers in order to reconstruct the state from the measurements in the Fourier space. This work requires to solve preliminary modeling and identification problems involving computations that cannot, for the moment, be performed in real time. We propose a method inspired by Zwaan [76]. In his method, heart motion during breath-hold was studied with the assumption that each heartbeat is a rescaled copy of a standard heartbeat. Here, the same assumption is extended to respiratory motion. Similarly to the algorithm presented by Zwaan [76], our method is based on the properties of the Reproducing Kernel Hilbert Spaces (RKHS) [55], which provide a general and rigorous framework for handling interpolation problems, and have been widely used in signal and image processing. This framework is of particular relevance here, as retrospective gating can be reformulated as a scattered data interpolation in a 1D or 2D space. An interesting contribution to this topic has been brought by Cindea, in collaboration with specialists in medical imaging, has been published in [22].

6.4.2. Biology

Y. Privat and A. Henrot have considered the shape optimization problem for the lung. The questions which are studied are the following:

1. is the dichotomic structure of the lung tree and the dimension of each branch optimal?
2. is the cylindrical shape of a given branch optimal?

The state equation used for the modelling is the Navier-Stokes system with classical boundary condition. The criterion to be minimized is the dissipated energy. For the second question, the authors prove that the cylinder is NOT the optimal shape. This result is interesting both from a practical point of view (think to pipes) and for a theoretical point of view. Actually, there are a very few theoretical results for shape optimization problems in fluid mechanics even if it is a topic extensively studied because of its potential applications. This study has been published in [25].

7. Contracts and Grants with Industry

7.1. ANR

Participant:

As mentioned in the highlights, 2009 was outstanding for CORIDA in terms of ANR grants. More precisely the following new projects have been funded:

- CISIFS (Control of Fluid-structure Interactions), coordinated by Lionel Rosier and Takéo Takahashi: 90500 euros for 4 years ;
- MICROWAVES (Microlocal Analysis and Numerical Methods for Wave Propagation), coordinated by Xavier Antoine: 103000 euros for 4 years;
- GAOS (Geometric Analysis of Optimal Shapes), with Antoine Henrot local coordinator: 83130 euros for 3 years;
- GCM (Geometric Control Methods), with Mario Sigalotti local coordinator: 129266 euros for 4 years.

Moreover we continued our activities connected to the existing ANR grants

- 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.
- Contrôle Flux:this ANR project (2006-2009) is devoted to the control of fluids and of fluid-structure interactions.
- 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;

8. Other Grants and Activities

8.1. National initiatives

8.1.1. Administrative responsibilities

- At INRIA: Tucsnak is member of the Executive Team and of the Project Committee of the INRIA Nancy-Grand Est Research Centre.
- In the Universities and in CNRS committees:
  - Henrot is the head of the Institut Élie Cartan de Nancy (IECN).
  - Tucsnak is member of the Scientific Council of UHP.
  - Alabau is member of CNU, section 26.
  - Our team is part of the GDR entitled “Fluid-Structure Interactions”.

8.1.2. National projects

- CPER (“Contrat Plan Etat Région”):
  - Serres, Sigalotti (leader) and Vivalda 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.

- ANR (“Agence Nationale de la recherche”):
  - Munnier, Scheid, Takahashi and Tucsnak are in the ANR project “MOSICOB” (“ANR Blanche”) for three years in collaboration with the University of Paris Sud and with the University of Grenoble.
  - Rosier and Takahashi are in the ANR project “Contrôle d’équations aux dérivées partielles en mécanique des fluides” (in collaboration with the University of Paris 6, the University of Versailles and the University of Nanterre).
- Our team is part of the GDR entitled “Fluid-Structure Interactions”.

8.2. Associated Team

The CORIDA project is linked with a group of the University of Chile through the associated team ANCIF.

8.3. Bilateral agreements

1. A IFCPAR grant with the Tata Institute (Bengalooru, India).
2. A “Partenariat Hubert Curien” (PHC) with the IST (Lisbon, Spain).
3. A “Partenariat Hubert Curien” (PHC) with the Mathematical Institute of the Academy of Sciences of the Czech Republic (Prague).

8.4. Visits of foreign researchers

Evans Harrell (Georgia Tech, Atlanta), Gérard Philippin (U. Laval, Québec), George Weiss (Imperial College, London, England), Ana Leonor Silvestre and Carlos Alves (IST Lisbon, Portugal), M. Kesavan and M. Vaninnathan (India).

9. Dissemination

9.1. Participation to International Conferences and Various Invitations

9.1.1. Organization of Conferences

- Antoine Henrot organized the International Workshop “Partial Differential Equations and Applications” in Vittel, France, October 22–24, 2009.

9.1.2. Invitations to international conferences and workshops

- Antoine
  - Workshop “Computational Electromagnetism and Acoustic”, Oberwolfach, Germany, February 2009.
  - 10th Days of “Calcul Scientifique et Modélisation Mathématique”, LAMFA, Amiens, June 2009.
  - Mini-symposium “High-Order Methods for Linear and Nonlinear Wave Equations”, 9th International Conference on Spectral and High Order Methods: ICOSAHOM09, Trondheim, Norway, June 22-26, 2009.
  - Mini-symposium “High Frequency Wave Propagation”, 8th European Conference on Numerical Mathematics and Advanced Applications, Uppsala University, Sweden, June 29 - July 3, 2009.
  - Special Session “Multiple Scattering: from Theory to Application”, 158th Meeting of the Acoustical Society of America, San Antonio, Texas, Octobre 2009.

- Henrot
  - Workshop “Low Eigenvalues of Laplace and Schroedinger Operators”, Oberwolfach, Germany, February 2009.
  - Conference “PDE’s, Optimal Design and Numerics II”, Benasque, Spain, August 2009.
- Munnier
  - Organizer of the minisymposium “Sur la nage des poissons : analyse mathématique et simulations numériques”, Congrès SMAI 2009.
  - Invitation in the framework of CONICIT (Spanish governmental research agency), Madrid, January 2009.
- Ramdani
  - Workshop “Design of Gratings and Inverse Scattering Theory”, University of Karlsruhe, Germany, October 2009.
- Rosier
  - International Conference on Mathematical Control Theory, Beijing (China), May 15-17, 2009.
  - 27^{O} Colóquio Brasileiro de Matemática, IMPA, Rio de Janeiro (Brazil), July 27-31, 2009.
  - School and Workshop on Partial Differential Equations, Optimal Design and Numerics III, Benasque (Spain), August 24 - September 3, 2009.
  - Workshop: Control and Inverse Problems of Systems Governed by PDEs, Sevilla (Spain), September 28-30, 2009.
- Takahashi
  - Workshop “Control and Inverse Problems of Systems Governed by PDE’s”, Sevilla, Spain, September 28-30, 2009.
- Tucsnak
  - International Conference on Mathematical Control Theory, May 15–17, 2009, Academy of Mathematics and Systems Sciences, Chinese Academy of Sciences (CAS), Beijing, China.
  - 1st Workshop of the European Research Group project “Control of Partial Differential Equation”, Institut Henri Poincaré, Paris, October 2009.
- Valein
  - 1st Workshop of the European Research Group project “Control of Partial Differential Equation”, Institut Henri Poincaré, Paris, October 2009.
- Vivalda
  - Invitation to the “Colloque international sur les systèmes dynamiques distribués et contrôle”, Oum El Bouaghi (Algeria), 8–10, November 2009.

9.1.3. Invitations

- Alabau
  - One week invitation at Univ. of Monastir, Tunisia, December 2008.
- Henrot
  - 5 months from January to May 2009 in Georgia Tech, Atlanta, invited by Evans Harrell and Michael Loss.
  - One week in Lisbon in July 2009, invited by Prof. Pedro Freitas.

- Rosier
  - IMPA (Rio de Janeiro, Brasil), July 26-August 13, 2009. Invitation of Prof. Felipe Linares.

9.1.4. Seminars

- Antoine
  - Seminar of the Mathematics Laboratory of Metz (LMAM), January 2009.
- Henrot
  - PDE Seminar of the University of Illinois at Urbana-Champaign, January 2009.
  - Research Seminar of the Math Department of Georgia Tech, January 2009.
- Munnier
  - PDE's seminar of the University of British Columbia (Vancouver, Canada).
- Ramdani
  - University of Göttingen, *Colloquium of the Institute for Numerical and Applied Mathematics*, November 2009.

9.1.5. Participation to conferences

- Chambrion
  - International conference on Mathematical Control Theory and Mechanics, July 3–7, 2009, Suzdal, Russia.
  - 4th International Scientific Conference on Physics and Control, September 1–4, 2009, Catane, Italy. Presentation of [45].
  - 48th IEEE Conference on Decision and Control, December 16–18, 2009, Shanghai, China. Presentation of [46], [47] and [49].
- Klein, Pinçon, Ramdani and Thierry
  - 9th International Conference on Mathematical and Numerical Aspects of Waves (WAVES'09), Pau, June 2009.
- Ramdani
  - Control and Inverse Problems in PDE's – Theoretical and Numerical Aspects, CIRM Conference, February 2009.
- Valein
  - IFAC Workshop on Control of Distributed Parameter Systems, Toulouse, France, July 2009.
  - Workshop "Partial differential equations, optimal design and numerics", Benasque, Spain, August 2009

9.1.6. Editorial activities and scientific committee's memberships

- Tucsnak
  - Associated editor of "SIAM Journal on Control" and of "ESAIM COCV".
  - Member of the Scientific Committee of PICOF'09

9.2. 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 (Munnier, Pinçon and Ramdani);
- Semigroups and evolution equations in Hilbert spaces (Tucsnak).

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