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# Activity Report 2012

# 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 [65]), multiplier methods (cf. Lions [62]) or micro-local analysis techniques (cf. Bardos–Lebeau–Rauch [55]). 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 of the Year

BEST PAPER AWARD :

[45] **Model predictive real-time controller for a low-consumption electric vehicle in 2nd International Symposium on Environement-Friendly Energies and Applications, EFEA 2012**. T. MANRIQUE-ESPINDOLA, H. MALAISE, M. FIACCHINI, T. CHAMBRION, G. MILLÉRIOUX.

# 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, Takeo 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 [59] and the references therein). The feedback control of fluid motion has also been recently investigated by several research teams (see, for instance Barbu [54] 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 [63]. This characterization can be related to the Hautus criterion in the theory of finite dimensional systems (cf. [58]). 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 [64]. Using the result of Miller, K. Ramdani, T. Takahashi, M. Tucsnak have obtained in [5] a new spectral formulation of the criterion of Liu [63], which is valid for boundary control problems. This frequency test can be seen as an observability condition for packets of eigenvectors of the operator. This frequency test has been successfully applied in [5] to study the exact controllability of the Schrödinger equation, the plate equation and the wave equation in a square. Let us emphasize here that one further important advantage of this frequency approach lies in the fact that it can also be used for the analysis of space semi-discretized control problems (by finite element or finite differences). The estimates to be proved must then be uniform with respect to **both the frequency and the mesh size**.

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

### *3.2.2. Time-reversal*

The second area in which we make use of frequency tools is the analysis of time-reversal for harmonic acoustic waves. This phenomenon described in Fink [56] 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 [57]. 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, 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 [61] , 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 [66]. In the case of systems governed by linear PDE's some similar estimates have been obtained only very recently (see, for instance Miller [64]). 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 [53]).

## 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 Tcheougoue Tebou – Zuazua [67], 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. [68]. 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. [60], 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:** Takeo 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++

## 5.2. Fish locomotion in perfect fluids with potential flow

**Participants:** Alexandre Munnier [correspondant], Marc Fuentes, Bruno Pinçon.

SOLEIL is a Matlab suite to simulate the self-propelled swimming motion of a single 3D swimmer immersed in a potential flow. The swimmer is modeled as a shape-changing body whose deformations can be either prescribed as a function of time (simulation of the direct swimming problem) or computed in such a way that the swimmer reaches a prescribed location (control problem). For given deformations, the hydrodynamical forces exerted by the fluid on the swimmer are expressed as solutions of 2D integral equations on the swimmer's surface, numerically solved by means of a collocation method.

SOLEIL is free, distributed under licence GPL v3. More details are available on the project web page http://soleil.gforge.inria.fr/.

The next step of SOLEIL (under progress) is to take into account a fluid whose flow is governed by Stokes equations.

- Version: 0.1
- Programming language:Matlab/C++

# 6. New Results

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

In [38], a new characteristics method for the discretization of the two dimensional fluid-rigid body problem is proposed in the case of different densities for the fluid and the solid. Convergence results are obtained for a fully-discrete finite element scheme.

In [35], controllability results are obtained for a low Reynolds number swimmer. The swimmer is undergoing radial and axi-symmetric deformations in order to propel itself in a viscous fluid.

The aim of the paper [51] is to tackle the time optimal controllability of an (n+1)-dimensional nonholonomic integrator. A full description of the optimal control and optimal trajectories are explicitly obtained.

In [25], we the interaction between a viscous incompressible fluid and an elastic structure immersed in the fluid.

In [30], weconsider the model composed by a rigid body immersed into a n incompressible perfect fluid and analyze the regularity of the trajectory of the rigid body and of the fluid particles.

In [39], we study the motion of a rigid body with a cavity filled with a viscous liquid.

In [34], we analyze a model of vesicle moving into a viscous incompressible fluid.

In [27], we obtain the identifiability of a rigid body moving in a stationary viscous fluid.

In [40] we study a mathematical model for the dynamics of vesicle membranes in a 3D incompressible viscous fluid. we show that, given $T > 0$, for initial data which are small (in terms of $T$), these solutions are defined on $[0, T]$ (almost global existence).

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

In [21] and [20], we propose an asymptotic analysis for the simple layer potential for multiple scattering at low frequencies.

In [19] 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 [32], we are concerned with the convergence analysis of the iterative algorithm for solving initial data inverse problems from partial observations that has been recently proposed in Ramdani et al. More precisely, we provide a complete numerical analysis for semi-discrete (in space) and fully discrete approximations derived using finite elements in space and an implicit Euler method in time. The analysis is carried out for abstract Schrödinger and wave conservative systems with bounded observation (locally distributed).

In [23], we propose a strategy to determine the Dirichlet-to-Neumann (DtN) operator for infinite, lossy and locally perturbed hexagonal periodic media, using a factorization of this operator involving two non local operators. The first one is a DtN type operator and corresponds to a half-space problem, while the second one is a Dirichlet-to-Dirichlet (DtD) type operator related to the symmetry properties of the problem.

In [18], we investigate absorbing boundary conditions for the two-dimensional Schrödinger equation with a time and space varying exterior potential.

## 6.3. Observality, controllability and stabilzation in the time domain

In [17] 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 [37] 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 [12], we consider the approximation of two coupled wave equations with internal damping. Our goal is to damp the spurious high frequency modes by introducing a numerical viscosity term in the approximation schemes and prove the exponential or polynomial decay of the discrete scheme.

In [13], we show similar results as in [12] for an abstract second order evolution equations.

In [44] we consider a class of infinite dimensional systems involving a control function $u$ taking values in $[0, 1]$ and we prove, when $u$ is given in an appropriate feedback form and the system satisfies appropriate observability assumptions, that the system is weakly stable. The main example concerns the analysis and stabilization of a model of Boost converter connected to a load via a transmission line.

In [46] 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 [41], 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 [15], we give a constructive proof of Gibson's stability theorem, some extension and further positive and negative applications of this result.

In [36] we prove that the boundary controls for the heat equation have the bang-bang property, at least in rectangular domains. This result is proved by combining methods from traditionally distinct fields: the Lebeau-Robbiano strategy for null controllability and estimates of the controllability cost in small time for parabolic systems, on one side, and a Remez-type inequality for Muntz spaces and a generalization of Turan's inequality, on the other side.

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.

In [14], we prove controllability results for abstract systems of weakly coupled N evolution equations in cascade by a reduced number of boundary or locally distributed controls ranging from a single up to N-1 controls. We give applications to cascade coupled systems of N multi-dimensional hyperbolic, parabolic and diffusive (Schrödinger) equations. The results are valid for control and coupling regions which do not necessarily intersect.

In [22], we study two notions of controllability, called respectively radial controllability and directional controllability. We prove that for families of linear vector fields, the two notions are actually equivalent.

In [24] we solve an optimization problem in convex geometry which, despite its seeming simplicity, offers a nice variety of solutions, some of them being unexpectable.

The paper [28] is devoted to prove that the union of two identical balls minimizes a non linear eigenvalue (related to the generalized Wirtinger inequality) among sets of given volume.

In [33] is considered a problem in population dynamics where we investigate the question of optimal location of the zone of control.

In [26], we give a rigorous proof, valid also for unbounded operators, of the widely used “rotating wave approximations” for bilinear Schrödinger equations.

In [42], we exploit the results of [26] on standard examples of bilinear quantum systems.

# 7. Bilateral Contracts and Grants with Industry

## 7.1. 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).

## 7.2. 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. National Initiatives

Alexandre Munnier, Jean-François Scheid (co-leader), Takéo Takahashi and Marius Tucsnak are members of the project CPER AOC-MISN "Autopropulsion dans un Fluide à bas Reynolds" (AFR). Collaborative project with the CRAN laboratory (Centre de Recherche en Automatique de Nancy).

### *8.1.1. ANR*

Most of the members of our team are involved at least one ANR program.

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

Antoine Henrot is head of the ANR blanc project OPTIFORM since September 2012 . This project is devoted to the Geometric Analysis of Optimal Shapes. It gathers scientist from Grenoble, Chambéry, Lyon, Rennes and Paris Dauphine. This ANR project will be active up to August 2016.

# 9. Dissemination

## 9.1. Scientific Animation

Most of the members of the team are regular reviewers of major journals of the field and participate to major conferences. We give here below a selection of our other activities or responsabilities.

- Xavier Antoine and Karim Ramdani were members of the organizing committee of the “Journées de Metz 2012”.
- Fatiha Alabeau is member of the National Committee of the CNRS, section 41, member of the AERES committees for the CEREMADE (University Paris-Dauphine) and MAP5 (University Paris Descartes) and member of the Administration Council of the S.MA.I., was member of the organizing commitee of MCPIT2013 "Modelling, Control and Inverse Problems for the Planet Earth in all its states", Conference of the GDRE CONEDP and for “Mathematics of the Planet Earth, co-organisation”, november 18–23 2013, Institut Henri Poincaré, Paris, France and of the thematic school of the CNRS, GDRE CONEDP, “Control of PDEs, interactions and applicative challenges”, november 5–9 2012, CIRM Luminy, France, and is member of the editorial board of the journal Evolution Equations and Control Theory (EECT), American Institute of Mathematics and Sciences (AIMS)
- Antoine Henrot is 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), elected to the Administrative Council of the University of Lorraine in June 2012, and scientific Delegate for Mathematics at AERES (the French Agency for Evaluation of Research) since September 2012.
- Marius Tucnsak became senior Member of Institut Universitaire de France in 2012 and is member of the editorial boards of ESAIM COCV, Journal of Mathematical Fluid Dynamics (New) and Revue Roumaine de Mathématiques Pures et Appliquées (New).

## 9.2. Teaching - Supervision - Juries

### *9.2.1. Teaching*

Most of the members of the team have a teaching position (192 hours a year) in Université de 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. Supervision

PhD : [11] Ghislain HAINE, “Observateurs en dimension infinie. Application à l’étude de quelques problèmes inverses”, Université de Lorraine, October 22, 2012. Supervisor: Karim Ramdani.

PhD: Jérôme Lohéac, “Contrôle en temps optimal et nage à bas nombre de Reynolds”, Université de Lorraine, December 6th, 2012. Supervisors: Marius Tucsnak and Jean-François Scheid (IECN and EPI Corida).

PhD in progress : Tatiana Manrique, “Stratégies efficaces pour la commande de véhicules hybrides”, Université de Lorraine. Supervisors: Gilles Millerioux (CRAN, Université de Lorraine) and Thomas Chambrion (IECN and EPI Corida).

PhD in progress: Chi Ting Wu, title not available yet, Université de Lorraine. Supervisors: Marius Tucsnak and Julie Valein (IECN and EPI Corida).

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# Publications of the year

## Doctoral Dissertations and Habilitation Theses

[11] G. HAINE. *Observateurs en dimension infinie. Application à l'étude de quelques problèmes inverse*, Université de Lorraine, 2012.

## Articles in International Peer-Reviewed Journals

[12] F. ABDALLAH, S. NICAISE, J. VALEIN, A. WEHBE. *Stability results for the approximation of weakly coupled wave equations*, in "Comptes Rendus de l Académie des Sciences - Series I - Mathematics", 2012, vol. 350, n° 1-2, p. 29-34.

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