Activity Report 2014

Team CORIDA

Robust control of infinite dimensional systems and applications

Table of contents

Team CORIDA

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

The Laboratoire de Mathématiques et Applications de Metz (LMAM) and the Institut Élie Cartan de Nancy (IECN) have been merged in Institut Élie Cartan de Lorraine (IECL) in January 2013.

Creation of the Project-Team: 2002 October 01, *updated into Team:* 2014 January 01.

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2. Overall Objectives

2.1. Overall Objectives

CORIDA is a team labeled by Inria, by CNRS and by Université de Lorraine (formerly University Henri Poincaré), via the Institut Élie Cartan of Lorraine UMR 7502 (formerly 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 [58]), multiplier methods (cf. Lions [55]) or micro-local analysis techniques (cf. Bardos–Lebeau–Rauch [48]). 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.

3. Research Program

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

Participants: Thomas Chambrion, Antoine Henrot, Alexandre Munnier, Lionel Rosier, Jean-François Scheid, 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 [52] and the references therein). The feedback control of fluid motion has also been recently investigated by several research teams (see, for instance Barbu [47] 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 [59]. Another important result gives the existence and the uniqueness of strong solutions for two or three-dimensional Navier–Stokes fluid [61]. 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.

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 [56]. This characterization can be related to the Hautus criterion in the theory of finite dimensional systems (cf. [51]). 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 [57]. Using the result of Miller, K. Ramdani, T. Takahashi, M. Tucsnak have obtained in [5] a new spectral formulation of the criterion of Liu [56], 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 [49] 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 [50]. 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-Boussouira, 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 [54], 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 [60]. In the case of systems governed by linear PDE's some similar estimates have been obtained only very recently (see, for instance Miller [57]). 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 [46]).

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 [62], for optimal and robust control problems.

4. Application Domains

4.1. Biology and Medicine

4.1.1. 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. [63]. 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. [53], 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. Simulation of viscous fluid-structure interactions

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

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

4.3. 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) is a collection of M-Files for design, simulation and analysis of articulated bodies' motions in fluid. More widely, BHT allows also to perform easily any kind of numeric experiments addressing the motion of solids in ideal fluids (simulations of so-called fluid-structure interaction systems).

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

5. New Software and Platforms

5.1. Simulation of viscous fluid-structure interactions

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

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 developed by ALICE.

- Version: v0.5
- Programming language: MATLAB/C++

5.2. Fish locomotion in perfect fluids with potential flow

Participants: Alexandre Munnier [correspondant], 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++

5.3. SUSHI3D : SimUlations of Structures in Hydrodynamic Interactions

Participants: Jean-François Scheid, Takéo Takahashi.

SUSHI3D is a 3D solver for numerical simulations of Fluid/Structures Interactions. The Navier-Stokes equations are coupled with the dynamics of immersed bodies which can be either rigid or deformable. The deformable body case is handled and designed for fish-swimming. The numerical method used to solve the full differential system is based on a Lagrange-Galerkin method with finite elements.

- Version: 1.0
- Programming language:Matlab/C++

5.4. The Vir'Volt prototype

Participants: Thomas Chambrion, Bruno Pinçon.

The European Shell Eco Marathon is an annual competition gathering around 200 high schools and universities. The aim of this race is to travel a given distance (changing from year to yearn, about 16 km in 2013 and 2014) within a given time (39 minutes in 2014). The winning team is the one with the lowest energy consumption (expressed in km/kWh). The EcoMotion Team (EMT) of the École Supérieure des Sciences et Technologies de l'Ingénieur de Nancy (ESSTIN) in France, has been involved for 15 years in the European Shell Eco-Marathon in the categories gasoline, hydrogen and battery electric. In 2014, the prototype *Vir'Volt 3* (see Figure 1) entered the competition in the battery electric category.

Figure 1. Vir'Volt prototype during a test run in Geoparc race track near Saint Dié in May 2014 (left) and in the neighborhood of Toul in October 2014 (right).

An automatic speed control was embedded in the vehicle. From the velocity measures and a GPS sensor, the dynamics was identified in real time. This identification was precise enough to detect changes in the slope of the track or in wind direction. This dynamics was then used to compute in real time an optimal pair of lower and upper bounds for the speed. These bounds were computed in real time with an embedded low cost micro-controller. The final performance [1] of 533 km/kWh is in line with the (human driven) performance of the team in the recent years.

6. New Results

6.1. Highlights of the Year

The CORIDA team organized two scientific meetings in 2014.

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[1]http://s00.static-shell.com/content/dam/shell-new/local/corporate/ecomarathon/downloads/pdf/europe/2014-results/sem-europe-2014-results-prototype-battery-electric-220514.pdf

The first workshop, "Observers for finite and infinite dimensional systems" in April 2014, gathered people working in the field of control theory for finite and infinite dimensional systems.

Ten speakers from France, India, Portugal and Germany were invited for the second workshop, "Workshop in Mathematical Fluid Dynamics", in November 2014.

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

In [42], we consider a two dimensional collision problem for a rigid solid immersed in a cavity filled with a perfect fluid. we investigate the asymptotic behavior of the Dirichlet energy associated to the solution of a Laplace Neumann problem as the distance between the solid and the cavity's bottom tends to zero. We prove that the solid always reaches the cavity in finite time. The contact occurs with non zero (real shock) or null velocity velocity (smooth landing), depending on the tangency exponent at the contact point. The proof is based on a suitable change of variables sending to infinity the cusp singularity at the contact. More precisely, the initial Laplace Neumann problem is transformed into a generalized Neumann problem set on a domain containing a horizontal strip, whose length goes to infinity as the the solid gets closer to the the cavity's bottom.

In [43], we investigate the geometric inverse problem of determining, from the knowledge of the DtN operator of the problem, the positions and the velocities of moving rigid solids in a bounded cavity filled with a perfect fluid. We assume that the solids are small disks moving slowly. Using an integral formulation, we first derive the asymptotic expansion of the DtN map as the diameters of the disks tend to zero. Then, combining a suitable choice of exponential type data and the DORT technique (which is usually used in inverse scattering for the detection of point-like scatterers), we propose a reconstruction method for the unknown positions and velocities.

In [22], Ana Leonor Silvestre (Lisbon, Portugal) and Takéo Takahashi analyze the system fluid-rigid body in the case of where the rigid body is a ball of "small radius". More precisely, they consider the limit system as the radius goes to zero. They recover the Navier-Stokes system with a particle following the the velocity of the fluid.

In [14], Mehdi Badra (University of Pau) and Takéo Takahashi study the feedback stabilization of a system composed by an incompressible viscous fluid and a rigid body. They stabilize the position and the velocity of the rigid body and the velocity of the fluid around a stationary state by means of a Dirichlet control, localized on the exterior boundary of the fluid domain and with values in a finite dimensional space. The first result concerns weak solutions in the two-dimensional case, for initial data close to the stationary state. The method is based on general arguments for stabilization of nonlinear parabolic systems combined with a change of variables to handle the fact that the fluid domain of the stationary state and of the stabilized solution are different. This additional difficulty leads to the assumption that the initial position of the rigid body is the position associated to the stationary state. Without this hypothesis, they work with strong solutions, and to deal with compatibility conditions at the initial time, they use finite dimensional dynamical controls. They prove again that for initial data close to the stationary state, they can stabilize the position and the velocity of the rigid body and the velocity of the fluid.

In [15], Mehdi Badra (University of Pau) and Takéo Takahashi use the Fattorini criterion (more known as the Hautus criterion) to obtain the feedback stabilizability of general linear and nonlinear parabolic systems. They then consider flow systems described by coupled Navier-Stokes type equations (such as MHD system or micropolar fluid system) to obtain the stabilizability by only considering a unique continuation property of a stationary Stokes system.

In [36], we use geometric control theory to investigate the existence and the design of optimal strokes for swimmers in Stokes of potential flows.

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

In [20], we use microlocal analysis techniques to build artificial boundary conditions for reltivistic quantum dynamics.

In [11], we give a complete analysis of some new domain decomposition techniques and investigate their approximations for application in quantum physics.

In the chapter [28], we give an introduction to the modeling and the simulation of equilibrium states of Gross-Pitaevskii equations modeling Bose-Einstein condensates.

In [17], we give the basic methodology to use the software 3D GPELab for the simulation of Bose-Einstein condensates.

In [10], we develop a pseudo-spectral iterative method to compute equilibrium state of fast rotating Gross-Pitaevskii equations.

In [18], we develop a new approximation and implementation of a Magnetic-to-Electric operator for 3D-Maxwell equations.

In [13], we consider the inverse problem of determining the potential in the dynamical Schrödinger equation on the interval by the measurement on the boundary. Using the Boundary Control Method we first recover the spectrum of the problem from the observation at either left or right end points. Taking advantage of the one-dimensional configuration, we recover then the spectral function, reducing the problem to the classical one of determining the potential from the spectral function. This can be done by known methods. In order to handle more realistic situations, we also consider the case where only a finite number of eigenvalues are available and we prove the convergence of the reconstruction method as this number tends to infinity.

6.4. Observality, controllability and stabilization in the time domain

In [27], we dealt with the problem of the stabilization of a switched linear system, the feedback law being based on the optimization of a quadratic criterion. The Lyapunov function used for the design of this law defines a tight upper bound of the value of the cost for a quadratic optimization problem related to the system. Thus the obtained control law is sub-optimal.

In [19] we deal with the problem of the output stabilization of linear impulsive systems. These system are a mix of continuous and discrete-time system. An observer is synthesized and the stabilization is ensured through a feedback law which depends on the estimated state provided by the observer.

In [29], we consider the design an high gain observers for a class of continuous dynamical systems with discrete-time measurements. In this work, the measurement sampling time is considered to be variable. Moreover, the new idea of the proposed work is to synthesize an observer requiring the less knowledge as possible from the output measurements. This is done by using an updated sampling time observer. Under the global Lipschitz assumption, the asymptotic convergence of the observation error is established. As an application of this approach, an state estimation problem of an academic bioprocess is studied, and its simulation results are discussed.

In [26], we propose an MPC control scheme for a linear system with real-time constraints.

In [25] and [12], we use precise energy estimates to provide an upper bound on the error made when replacing the dynamics of an infinite dimensional conservative quantum system by a finite dimensional projection.

In [34], we give a set of sufficient conditions for approximate controllability of closed quantum systems when the dipolar approximation has to be replaced by a more realistic quadratic modeling.

In [35], we investigate the regularity of propagators of bilinear control systems and extend a celebrated negative result of Ball, Marsden and Slemrod.

In [16], we consider an infinite dimensional system modelling a boost converter connected to a load via a transmission line. The governing equations form a system coupling the telegraph partial differential equation with the ordinary differential equations modeling the converter. The coupling is given by the boundary conditions and the nonlinear controller we introduce. We design a nonlinear saturating control law using

a Lyapunov function for the averaged model of the system. The main results give the well-posedness and stability properties of the obtained closed loop system.

7. Partnerships and Cooperations

7.1. National Initiatives

7.1.1. ANR

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

Marius Tucnsak is local coordinator of ANR blanc project Hamecmopsys. This ANR project will be active up to 2015.

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.

Xavier Antoine is coordinator for partner 2 of ANR blanc project BECASIM since September 2013. This ANR project will be active up to 2017.

7.1.2. GDR

Thomas Chambrion has been animator of the EDP group of GDR MAC since October 2014.

7.2. International Research Visitors

7.2.1. Visits of International Scientists

Prof Gengsheng Wang, University of Wuhan, China, visited our team for 3 months.

Prof George Weiss, University of Tel Aviv, Israel, visited our team for 1 month.

7.2.2. Visits to International Teams

Julie Valein has been invited for 3 months (October-December) in the Department of Applied Physics and Applied Mathematics (APAM) at Univeristy of Columbia, New-York, USA.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific events organisation

8.1.1.1. Organizing committee membership

In April 2014, CORIDA organized in Nancy a workshop on "Observers for finite and infinite dimensional systems" gathering people working in the field of control theory for finite and infinite dimensional systems.

Takéo Takahashi and Marius Tucsnak organized a workshop "Workshop in Mathematical Fluid Dynamics", in Nancy from November 26th-28th, 2014. There were 10 invited speakers from France, India, Portugal and Germany.

Marius Tucsnak is a member of the organizing Committee of SIAM Conference on Control, Paris 2015.

8.1.1.2. Conference program committee membership

Xavier Antoine was a member of the program committee for The Ninth International Conference on Engineering Computational Technology (ECT2014), Naples, Italy, 2-5 September 2014.

8.1.2. Journal

8.1.2.1. Editorial board membership

Jean-Claude Vivalda is an associate editor of the *Journal of Dynamical and Control Systems*.

Xavier Antoine is a member of the editorial board of the collection *Mathématiques Appliquées pour le Master* for SMAI/DUNOD Ed.

Marius Tucsnak is a member of the editorial board of *MCSS*, *Journal of Mathematical Fluid Mechanics*, *ESAIM COCV*, *Mathematical Reports* and *Revue Roumaine de Mathématiques Pures et Appliquées*

8.1.2.2. Reviewing activities

Most members of the team are reviewers for major journals in the field, including *Automatica*, *IEEE Transactions on Automatic Control*, *ESAIM Contrôle optimal et calcul des variations*, *SIAM Journal of Control*, *Journal of Functional Analysis*.

8.2. Teaching - Supervision - Juries

8.2.1. 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;
- Xavier Antoine has a full time full professor position at ENSEM;
- Thomas Chambrion has a full time associate professor position at ESSTIN;
- Antoine Henrot has a full time full professor position at ENSEM-Mines Nancy;
- Bruno Pinçon has a full time associate professor position at Telecom Nancy;
- Lionel Rosier has a full time full professor position at ESSTIN;
- Jean-François Scheid has a full time associate professor position at Telecom Nancy;
- Marius Tucsnak has a full time full professor position;
- Julie Valein has a full time associate professor position at ESSTIN.

We only detail below the teaching activities of the Inria researchers:

Master : Takahashi, *Résolution numérique des EDP*, 21 hours, Mines Nancy, France

Master : Takahashi, *Analyse numérique*, 18 hours, Mines Nancy, France

Master : Ramdani, *Analyse numérique*, 18 hours, Mines Nancy, France

8.2.2. Supervision

HdR : Thomas Chambrion, *Méthodes mathématiques pour la commande de systèmes mécaniques de dimension infinie*, Université de Lorraine, May 29 2014.

HdR: Jean-François Scheid, , Université de Lorraine, December 11 2014.

PhD : Tatiana Manrique, *Optimisation de stratégie de conduite d'un véhicule à basse consomatio,n sous contraintes temps réel*, Université de Lorraine, December 9 2014, supervisors: T. Chambrion and G. Millerioux.

PhD: Jérémy Dalphin, "Etude de fonctionnelles géométriques dépendant de la courbure par des méthodes d'optimisation de formes", Universite´ de Lorraine, December 5th, 2014. Supervisors: Antoine Henrot and Takéo Takahashi.

PhD in progress : Chi-Ting WU, since 2013. Supervisors: Marius Tucsnak and Julie Valein.

8.2.3. Juries

X. Antoine has been a member of the committee for A. Vion (PhD thesis, Univ. de Liège, Décembre 2014) and M. Darbas (HDR thesis, Amiens, Décembre 2014).

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