Activity Report 2013

Project-Team CORIDA

Robust control of infinite dimensional systems and applications

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

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 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 [60]), multiplier methods (cf. Lions [57]) or micro-local analysis techniques (cf. Bardos–Lebeau–Rauch [50]). 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

Marius Tucsnak has been nominated Senior Member of the Institut Universitaire de France.

George Weiss visited our team in the frame of the "Chercheur d'excellence" program of Région Lorraine.

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, 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 [55] and the references therein). The feedback control of fluid motion has also been recently investigated by several research teams (see, for instance Barbu [49] 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 [58]. This characterization can be related to the Hautus criterion in the theory of finite dimensional systems (cf. [53]). 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 [59]. Using the result of Miller, K. Ramdani, T. Takahashi, M. Tucsnak have obtained in [5] a new spectral formulation of the criterion of Liu [58], 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 [51] 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 [52]. 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 [56], 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 [61]. In the case of systems governed by linear PDE's some similar estimates have been obtained only very recently (see, for instance Miller [59]). 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 [48]).

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. Software and Platforms

4.1. 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++

4.2. 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++

4.3. SUSHI3D : SimUlations of Structures in Hydrodynamic Interactions

Participants: Marc Fuentes, Jean-François Scheid, Jérémy Sinoir, Takéo Takahashi, Rhaleb Zayer.

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. New Results

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

In [47], we analyze the system fluid-rigid body in the case of where the rigid body is a ball of "small radius". More precisely, we consider the limit system as the radius goes to zero. We recover the Navier-Stokes system with a particle following the the velocity of the fluid. We consider in [45] a model of vesicle moving into a viscous incompressible fluid. Such a model, based on a phase-field approach was derived by researchers in Physics, and is quite difficult to study. By considering some approximation, we prove some result of existence of solutions for such a system.

By acting on a part of the fluid domain or on a part of the exterior boundary, we aim at controlling the fluid velocity, the rigid velocity and the position of the rigid body. It can be a control in open loop or in closed loop. We have studied both problems in the 1D case. In this case, the study benefits some simplifications, but can also be more difficult since the fluid domain is no more connected. As a consequence, if one wants to control by using only one input, on one part of the fluid domain, the fluid on the other side of the particle is only controlled by the motion of the structure.

We introduce a new method for controllability of nonlinear parabolic system allowing to deal with this problem and we solve it in ([24]). We also obtain the local stabilization of such system around a stationary state in [41].

We study the Cauchy problem corresponding to a similar 1D system without viscosity in [40]. In that case, we have to deal with the interaction between the particle and shock waves or relaxation waves. In [44], we analyze a numerical scheme for the method of observers used to reconstruct the initial data of hyperbolic systems such as wave equation. We add some numerical viscosity in the scheme in order to have a uniform decay of the error between the reconstructed solution and the real one.

In [30], a Lagrange-Galerkin method is introduced to approximate a two dimensional fluid-structure inter-action problem for deformable solids. The new numerical scheme we present is based on a characteristics function mapping the approximate deformable body at the discrete time level t_{k+1} into the approximate body at time t_k.

The aim of [25] is to tackle the time optimal controllability of an $(n + 1)$-dimensional nonholonomic integrator with state constraints. A full description of an optimal control together with the corresponding optimal trajectories are explicitly obtained. The optimal trajectories we construct, are composed of arcs of circle lying in a 2-dimensional plane.

In [26], controllability results are obtained for a low Reynolds number swimmer composed by a spherical object which is undergoing radial and axi-symmetric deformations in order to propel itself in a viscous fluid governed by the Stokes equations. A time optimal control problem is also solved for a simplified model and explicit optimal solutions are constructed.

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

With a numerical viscosity terms in the approximation scheme of second order evolution equations, we show in [11] the exponential or polynomial decay of the discrete scheme when the continuous problem has such a decay and when the spectrum of the spatial operator associated with the undamped problem satisfies the generalized gap condition. We further show the convergence of the discrete solution to the continuous one.

In [19], 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 [22], we generalize to the case of acoustic penetrable scatterers the results derived by Hazard and Ramdani [54] for sound hard scatterers. In particular, we provide a justification of the DORT method in this case and we show that each small inhomogeneity gives rise to $3d + 1$ eigenvalues of the time reversal operator. The selective focusing of the corresponding eigenfunctions is also proved.

In [17], we consider the inverse problem of determining the potential in the dynamical Schrödinger equation on the interval by the measurement on the boundary. We use the Boundary Control Method to recover the spectrum of the problem from the observation at either left or right end points. Using the specificity of the one-dimensional situation we recover the spectral function, reducing the problem to the classical one which could be treated by known methods. We also consider the case where only a finite number (N) of eigenvalues are available and we prove the convergence of the reconstruction method as N tends to infinity.

We give some spectral and condition number estimates of the acoustic single-layer operator for low-frequency multiple scattering in dense [15] and dilute [16] media.

5.3. Use of geometric techniques for the control of finite and infinite dimensional systems

The paper [31] deals with the design of high gain observers for a class of continuous dynamical systems with discrete-time measurements. The new idea of the this 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.

In [12], it is shown that, for a bilinear system, the property of observability is preserved after sampling provided that the controls take their values in a compact space and do not vary too quickly.

In the note [18] two notions of controllability are studied, called respectively radial controllability and directional controllability. It is proven that for families of linear vector fields, the two notions are actually equivalent.

We used operators theory to obtain some new estimates of the energy of an infinite dimensional bilinear quantum systems. These results were presented in [34].

Robust control of bilinear Schrödinger equation was investigated in [35]. The use of sharp finite dimensional energy estimates (in the spirit of [34]) allows to obtain the first approximate ensemble controllability results for infinite dimensional quantum systems, also in presence of mixed spectrum for the free Hamiltonian.

The above energy questions, together with a their relation with some open question in the control of bilinear quantum systems, were gathered in the survey [32].

Our team is heavily involved in the optimization of driving strategy, and especially in the effective implementation in the prototype build in ESSTIN. MPC related methods have been tested and successfully improved as described in [37].

6. Partnerships and Cooperations

6.1. Regional Initiatives

In collaboration with B. Lévy (EPI ALICE), X. Antoine obtained a 25000 euros grant from Région Lorraine (projets émergents).

6.2. National Initiatives

6.2.1. ANR

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

Thomas Chambrion has been responsible for the quantum control part of the ANR blanc project GCM from 2009 to December 2013.

Marius Tucnsak is local coordinator of ANR blan 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.

6.3. International Initiatives

6.3.1. Inria International Partners

6.3.1.1. Informal International Partners

Most of the members of our team have regular collaborations with colleagues in abroad institutions.

Let us mention two new collaborations of Xavier Antoine with E. Lorin and A.D. Bandrauk (from Université de Carleton, Canada) and CRM, Montréal on one hand and with W. Bao (National University of Singapore) on the other hand. These two independent collaborations both deal with numerical computations in quantum mechanics (quantum chemistry and Bose-Einstein condensates).

6.4. International Research Visitors

6.4.1. Visits of International Scientists

George Weiss has been invited in our team for three months. This invitation was part of the " Chercheur d'excellence" program of Région Lorraine.

Ademir Fernando Pazoto visited our team during March 2013.

Fernando José Henriquez Barraza visited our team from February to June 2013.

6.4.2. Visits to International Teams

Marius Tucnsak was invited in the University of Wuhan (one month).

7. Dissemination

7.1. Scientific Animation

Most of the members of our team have regular editorial activities in the leading journals and conferences of the field.

For instance, Marius Tucnsak is a member of the editorial boards of ESAIM COCV, Journal of Mathematical Fluid Mechanics, Mathematical Reports and Revue Roumaine de Mathématiques Pures et Appliqués.

The notable changes with respect to 2012 are

- Xavier Antoine joined the editorial board of ISRN Applied Mathematics in 2013. He also became "délégué scientifique" in charge of the department "Mathematical sciences and Interactions" of the national funding agency ANR and was nominated head of the program "Accueil de Chercheuses et Chercheurs de Haut Niveau" in 2013.
- Thomas Chambrion joined the IFAC Technical Chair for control of PDE's in 2013.

7.2. Teaching - Supervision - Juries

7.2.1. *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 (Metz site);
- Xavier Antoine has a full time full professor position at École des Mines and ENSEM;
- Thomas Chambrion has a full time associate professor position at ESSTIN;
- Antoine Henrot has a full time full professor position at École des Mines;
- 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 NancyL;
- Marius Tucsnak has a full time full professor position at (Nancy site);
- Julie Valein has a full time associate professor position at ESSTIN.

7.2.2. *Supervision*

PhD in progress : Chi Ting Wu, "Approximations des problèmes de contrôle optimal", from 2012, Supervisor: Marius Tucsnak, co-supervisor: Julie Valein.

PhD in progress : Tatiana Manrique, "commande robuste de systèmes à commutations", from 2011, Supervisor: Gilles Millerioux (Université de Lorraine), co-supervisor: Thomas Chambrion.

PhD in progress : Ibrahim Zambre, "méthodes numériques hybrides en diffraction haute-fréquence", Supervisors: Xavier Antoine and Cristophe Guezaine (University of Liege).

7.2.3. *Juries*

Jean-François Scheid has been a PhD examiner for the thesis of S. Flotron - EPFL (Switzerland), april 2013.

Karim Ramdani has been member of the PhD juries Giovanni Migliorati (Ecole Polytechnique and Politechnico di Milano, april 2013) and of Alexandre Impériale (Paris 6 University, december 2013).

Marius Tucnsak was president of the PhD jury of Sarah MECHHOUD (Grenoble), referee for the PhD jury of Morgan MORANCEY (Ecole Polytechnique) and a member of the PhD jury of Pierre Lissy (Paris 6).

7.3. Popularization

In December 2013, Karim Ramdani organized with Estelle Carciofi a workshop dealing with issues related to scientific edition.

8. Bibliography

Major publications by the team in recent years

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