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Activity Report 2016

Project-Team SPHINX

Heterogeneous Systems: Inverse Problems, Control and Stabilization, Simulation

IN COLLABORATION WITH: Institut Elie Cartan de Lorraine (IECL)

RESEARCH CENTER
Nancy - Grand Est

THEME
Optimization and control of dynamic systems

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Creation of the Team: 2015 January 01, updated into Project-Team: 2016 May 01

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1. Members

Research Scientists

Takéo Takahashi [Team leader, Inria, Researcher, HDR]
Karim Ramdani [Inria, Senior Researcher, HDR]
Jean-Claude Vivalda [Inria, Senior Researcher, HDR]

Faculty Members

Xavier Antoine [Univ. Lorraine, Professor, HDR]
Thomas Chambrion [Univ. Lorraine, Associate Professor, HDR]
David Dos Santos Ferreira [Univ. Lorraine, Professor, HDR]
Julien Lequeurre [Univ. Lorraine, Associate Professor]
Alexandre Munnier [Univ. Lorraine, Associate Professor]
Jean-François Scheid [Univ. Lorraine, Associate Professor, HDR]
Julie Valein [Univ. Lorraine, Associate Professor]

PhD Students

Boris Caudron [Thales]
Chi-Ting Wu [Univ. Lorraine, until Sep 2016]

Post-Doctoral Fellows
Mohamed El Bouajaji [Univ. Lorraine, until Aug 2016]
Qinglin Tang [Rouen University, until Aug 2016]

Administrative Assistant
Céline Simon [Inria]

Others
Nicolas Ratto [Inria, Internship, from Mar 2016 until Aug 2016]
Arnab Roy [TIFR Bangalore, PhD Student, from Oct 2016 until Nov 2016]

2. Overall Objectives

2.1. Overall Objectives

In this project, we investigate theoretical and numerical mathematical issues concerning heterogeneous physical systems. The heterogeneities we consider result from the fact that the studied systems involve subsystems of different physical nature. In this wide class of problems, we study two types of systems: **fluid-structure interaction systems (FSIS)** and **complex wave systems (CWS)**. In both situations, one has to develop specific methods to take into account the coupling between the subsystems.

(FSIS) Fluid-structure interaction systems appear in many applications: medicine (motion of the blood in veins and arteries), biology (animal locomotion in a fluid, such as swimming fish or flapping birds but also locomotion of microorganisms, such as amoebas), civil engineering (design of bridges or any structure exposed to the wind or the flow of a river), naval architecture (design of boats and submarines, seeking of new propulsion systems for underwater vehicles by imitating the locomotion of aquatic animals). The FSIS can be studied by modeling their motions through Partial Differential Equations (PDE) and/or Ordinary Differential Equations (ODE), as is classical in fluid mechanics or in solid mechanics. This leads to the study of difficult nonlinear free boundary problems which constitute a rich and active domain of research over the last decades.

(CWS) Complex wave systems are involved in a large number of applications in several areas of science and engineering: medicine (breast cancer detection, kidney stones destruction, osteoporosis diagnosis, etc.), telecommunications (in urban or submarine environments, optical fibers, etc.), aeronautics (targets detection, aircraft noise reduction, etc.) and, in the longer term, quantum supercomputers. **For direct problems**, most theoretical issues are now widely understood. However, substantial efforts remain to be undertaken concerning the simulation of wave propagation in complex media. Such situations include heterogeneous media with strong local variations of the physical properties (high frequency scattering, multiple scattering media) or quantum fluids (Bose-Einstein condensates). In the first case for instance, the numerical simulation of such direct problems is a hard task, as it generally requires solving ill-conditioned possibly indefinite large size problems, following from space or space-time discretizations of linear or nonlinear evolution PDE set on unbounded domains. **For inverse problems**, many questions are open at both the theoretical (identifiability, stability and robustness, etc.) and practical (reconstruction methods, approximation and convergence analysis, numerical algorithms, etc.) levels.

3. Research Program

3.1. Control and stabilization of heterogeneous systems

Fluid-Structure Interaction Systems (FSIS) are present in many physical problems and applications. Their study involves to solve several challenging mathematical problems:

- **Nonlinearity:** One has to deal with a system of nonlinear PDE such as the Navier-Stokes or the Euler systems;

- **Coupling:** The corresponding equations couple two systems of different types and the methods associated with each system need to be suitably combined to solve successfully the full problem;
- **Coordinates:** The equations for the structure are classically written with Lagrangian coordinates whereas the equations for the fluid are written with Eulerian coordinates;
- **Free boundary:** The fluid domain is moving and its motion depends on the motion of the structure. The fluid domain is thus an unknown of the problem and one has to solve a free boundary problem.

In order to control such FSIS systems, one has first to analyze the corresponding system of PDE. The oldest works on FSIS go back to the pioneering contributions of Thomson, Tait and Kirchhoff in the 19th century and Lamb in the 20th century, who considered simplified models (potential fluid or Stokes system). The first mathematical studies in the case of a viscous incompressible fluid modeled by the Navier-Stokes system and a rigid body whose dynamics is modeled by Newton's laws appeared much later [108], [100], [79], and almost all mathematical results on such FSIS have been obtained in the last twenty years.

The most studied issue concerns the well-posedness of the problem modeling a **rigid body moving into a viscous incompressible fluid**. If the fluid fills the **unbounded domain** surrounding the structure, the free boundary difficulty can be overcome by using a simple change of variables that makes the rigid body fixed. One can then use classical tools for the Navier-Stokes system and obtain the existence of weak solutions (see, for instance, [67], [68], [101]) or strong solutions for the case of a ball [105]. When the rigid body is not a ball, the additional terms due to the change of variables modify the nature of the system and only partial results are available for strong solutions [69], [54], [102]. When the fluid-solid system is confined in a **bounded domain**, the above strategy fails. Several papers have developed interesting strategies in order to obtain the existence of solutions. Since the coupling is strong, it is natural to consider a variational formulation for both the fluid and the structure equations (see [57]). One can then solve the FSIS by considering the Navier-Stokes system with a penalization term taking into account the structure ([51], [99], [63]) or using a time discretization in order to fix the rigid body during some time interval ([73]). Using an appropriate change of variables has also been used (see [72], [104]), but of course, its construction is more complex than in the case where the FSIS fills the whole space. Most of the above results only hold up to a possible contact between two structures or between a structure and the exterior boundary. If the considered configuration excludes contacts, some authors also investigated the long-time behavior of this system and the existence of time periodic solutions [107], [89], [70].

Many other FSIS have been studied as well. Let us mention, for instance, **rigid bodies immersed in an incompressible perfect fluid** ([91], [76], [71]), **in a viscous compressible fluid** ([56], [44], [62], [45]), in a **viscous multipolar fluid** or in an **incompressible non-Newtonian fluid** ([64]). The case of **deformable structures** has also been considered, either for a fluid inside a moving structure (e.g. blood motion in arteries) or for a moving deformable structure immersed in a fluid (e.g. fish locomotion). Several models for the dynamics of the deformable structure exist: one can use the plate equations or the elasticity equations. The obtained coupled FSIS is a complex system and the study of its well-posedness raises several difficulties. The main one comes from the fact that we gather two systems of different nature, as the linearized problem couples a parabolic system with a hyperbolic one. Theoretical studies have been performed for approximations of the complete system, using two strategies: adding a regularizing term in the linear elasticity equations (see [49], [44], [82]) or approximate the equations of linear elasticity by a system of finite dimension (see [58], [47]). For strong solutions, the coupling between hyperbolic-parabolic systems leads to seek solutions with high regularity. The only known results [52], [53] in this direction concern local (in time) existence of regular solutions, under strong assumptions on the regularity of the initial data. Such assumptions are not very satisfactory but seem inherent in this coupling between two systems of different natures. Another option is to consider approximate models, but so far, the available approximations are not obtained from a physical model and deriving a more realistic model is a difficult task.

In some particular important physical situations, one can also consider a simplified model. For instance, in order to study self-propelled motions of structures in a fluid, like fish locomotion, one can assume that the **deformation of the structure is prescribed and known**, whereas its displacement remains unknown ([97]).

Although simplified, this model already contains many difficulties and permits to start the mathematical study of a challenging problem: understanding the locomotion mechanism of aquatic animals.

Using the above results and the corresponding tools, we aim to consider control or stabilization problems for FSIS. Some control problems have already been considered: using an interior control in the fluid region, it is possible to control locally the velocity of the fluid together with the velocity and the position of the rigid body (see [77], [46]). The strategy of control is similar to the classical method for a fluid (without solid) (see, for instance, [65]) but with the tools developed in [104]. A first result of stabilization was obtained in [93] and concerns a fluid contained in bounded cavity where a part of the boundary is modeled by a plate system. The feedback control is a force applied on the whole plate and it allows the author to obtain a local stabilization result around the null state.

To extend these first results of control and stabilization, we first have to make some progress in the analysis of FSIS:

- **Contact:** It is important to understand the behavior of the system when two structures are close, and in particular to understand how to deal with contact problems;
- **Deformable structures:** To handle such structures, we need to develop new ideas and techniques in order to couple two dynamics of infinite dimension and of different nature.

At the same time, we can tackle control problems for simplified models. For instance, in some regimes, the Navier-Stokes system can be replaced by the Stokes system and the Euler system by Laplace's equation

3.2. Inverse problems for heterogeneous systems

The area of inverse problems covers a large class of theoretical and practical issues which are important in many applications (see for instance the books of Isakov [78] or Kaltenbacher, Neubauer, and Scherzer [80]). Roughly speaking, an inverse problem is a problem where one attempts to recover an unknown property of a given system from its response to an external probing signal. For systems described by evolution PDE, one can be interested in the reconstruction from partial measurements of the state (initial, final or current), the inputs (a source term, for instance) or the parameters of the model (a physical coefficient for example). For stationary or periodic problems (i.e. problems where the time dependence is given), one can be interested in determining from boundary data a local heterogeneity (shape of an obstacle, value of a physical coefficient describing the medium, etc.). Such inverse problems are known to be generally ill-posed and their study leads to investigate the following questions:

- *Uniqueness.* The question here is to know whether the measurements uniquely determine the unknown quantity to be recovered. This theoretical issue is a preliminary step in the study of any inverse problem and can be a hard task.
- *Stability.* When uniqueness is ensured, the question of stability, which is closely related to sensitivity, deserves special attention. Stability estimates provides an upper bound for the parameter error given some uncertainty on data. This issue is closely related to the so-called observability inequality in systems theory.
- *Reconstruction.* Inverse problems being usually ill-posed, one needs to develop specific reconstruction algorithms which are robust with respect to noise, disturbances and discretization. A wide class of methods is based on optimization techniques.

In this project, we investigate two classes of inverse problems, which both appear in FSIS and CWS:

1. **Identification for evolution PDE.**

   Driven by applications, the identification problem for systems of infinite dimension described by evolution PDE has known in the last three decades a fast and significant growth. The unknown to be recovered can be the (initial/final) state (e.g. state estimation problems [38], [66], [74], [103] for the design feedback controllers), an input (for instance source inverse problems [35], [48], [59]) or a parameter of the system. These -linear or non linear- problems are generally ill-posed and many regularization approaches have been developed. Among the different methods used for identification, let us mention optimization techniques ([50]), specific one-dimensional techniques (like in [39]) or observer-based methods as in [87].

In the last few years, we have developed observers to solve initial data inverse problems for a class of linear systems of infinite dimension and of the form $\dot{z}(t) = Az(t)$ (A denotes here the generator of a C_0 semigroup) from an output $y(t) = Cz(t)$ measured through a finite time interval. Let us recall that observers (or Luenberger observers [86]) have been introduced in automatic control theory to estimate the state of a dynamical system (of finite dimension) from the knowledge of an output (and, of course, assuming that the initial state is unknown). Roughly speaking, an observer is an auxiliary dynamical system that uses as inputs the available measurements (that is the output of the original system) that converges asymptotically (in time) towards the state of the original system. Observers are very popular in the community of automatic control and have given rise to a wide literature (for more references, see for instance the book by O'Reilly [90] and more recently the one by Trinh and Fernando [106] devoted to functional observers). The generalization of observers (also called estimators or filters in the stochastic framework) to systems of infinite dimension goes back to the seventies (see for instance Bensoussan [42] or Curtain and Zwart [55]) and the theory is definitely less developed than in the case of finite dimension . Using observers, we have proposed in [92], [75] an iterative algorithm to reconstruct initial data from partial measurements for some evolution equations, including the wave and Schrödinger systems (and more generally for skew-adjoint generators). This algorithm also provides a new method to solve source inverse problems, in the case where the source term has a specific structure (separate variables in time-space with known time dependence). We are deepening our activities in this direction by considering more general operators or more general sources and the reconstruction of coefficients for the wave equation. In connection with this last problem, we study the stability in the determination of these coefficients. To achieve this, we use geometrical optics, which is a classical albeit powerful tool to obtain quantitative stability estimates on some inverse problems with a geometrical background, see for instance [41], [40].

2. **Geometric inverse problems.**

   We investigate some geometric inverse problems that appear naturally in many applications, like medical imaging and non destructive testing. A typical problem we have in mind is the following: given a domain Ω containing an (unknown) local heterogeneity ω, we consider the boundary value problem of the form

$$\begin{cases} Lu = 0, & (\Omega \setminus \omega) \\ u = f, & (\partial\Omega) \\ Bu = 0, & (\partial\omega) \end{cases}$$

   where L is a given partial differential operator describing the physical phenomenon under consideration (typically a second order differential operator), B the (possibly unknown) operator describing the boundary condition on the boundary of the heterogeneity and f the exterior source used to probe the medium. The question is then to recover the shape of ω and/or the boundary operator B from some measurement Mu on the outer boundary $\partial\Omega$. This setting includes in particular inverse scattering problems in acoustics and electromagnetics (in this case Ω is the whole space and the data are far field measurements) and the inverse problem of detecting solids moving in a fluid. It also includes, with slight modifications, more general situations of incomplete data (i.e. measurements on part of the outer boundary) or penetrable inhomogeneities. Our approach to tackle this type of problems is based on the derivation of a series expansion of the input-to-output map of the problem (typically the Dirchlet-to-Neumann map of the problem for the Calderón problem) in terms of the size of the obstacle.

3.3. Numerical analysis and simulation of heterogeneous systems

Within the team, we have developed in the last few years numerical codes for the simulation of FSIS and CWS. We plan to continue our efforts in this direction.

- In the case of FSIS, our main objective is to provide computational tools for the scientific community, essentially to solve academic problems.
- In the case of CWS, our main objective is to build tools general enough to handle industrial problems. Our strong collaboration with Christophe Geuzaine's team in Liege (Belgium) makes this objective credible, through the combination of DDM (Domain Decomposition Methods) and parallel computing.

Below, we explain in detail the corresponding scientific program.

- **Simulation of FSIS:** In order to simulate fluid-structure systems, one has to deal with the fact that the fluid domain is moving and that the two systems for the fluid and for the structure are strongly coupled. To overcome this free boundary problem, three main families of methods are usually applied to numerically compute in an efficient way the solutions of the fluid-structure interaction systems. The first method consists in suitably displacing the mesh of the fluid domain in order to follow the displacement and the deformation of the structure. A classical method based on this idea is the A.L.E. (Arbitrary Lagrangian Eulerian) method: with such a procedure, it is possible to keep a good precision at the interface between the fluid and the structure. However, such methods are difficult to apply for large displacements (typically the motion of rigid bodies). The second family of methods consists in using a *fixed mesh* for both the fluid and the structure and to simultaneously compute the velocity field of the fluid with the displacement velocity of the structure. The presence of the structure is taken into account through the numerical scheme. There are several methods in that direction: immersed boundary method, fictitious domain method, fat boundary method, the Lagrange-Galerkin method. Finally, the third class of methods consists in transforming the set of PDEs governing the flow into a system of integral equations set on the boundary of the immersed structure. Thus, only the surface of the structure is meshed and this mesh moves along with the structure. Notice that this method can be applied only for the flow of particular fluids (ideal fluid or stationary Stokes flow).

  The members of SPHINX have already worked on these three families of numerical methods for FSIS systems with rigid bodies (see e.g. [96], [81], [98], [94], [95], [88]). We plan to work on numerical methods for FSIS systems with non-rigid structures immersed into an incompressible viscous fluid. In particular, we will focus our work on the development and the analysis of numerical schemes and, on the other hand, on the efficient implementation of the corresponding numerical methods.
- **Simulation of CWS:** Solving acoustic or electromagnetic scattering problems can become a tremendously hard task in some specific situations. In the high frequency regime (i.e. for small wavelength), acoustic (Helmholtz's equation) or electromagnetic (Maxwell's equations) scattering problems are known to be difficult to solve while being crucial for industrial applications (e.g. in aeronautics and aerospace engineering). Our particularity is to develop new numerical methods based on the hybridization of standard numerical techniques (like algebraic preconditioners, etc.) with approaches borrowed from asymptotic microlocal analysis. Most particularly, we contribute to building hybrid algebraic/analytical preconditioners and quasi-optimal Domain Decomposition Methods (DDM) [43], [60], [61] for highly indefinite linear systems. Corresponding three-dimensional solvers (like for example GetDDM) will be developed and tested on realistic configurations (e.g. submarines, complete or parts of an aircraft, etc.) provided by industrial partners (Thales, Airbus). Another situation where scattering problems can be hard to solve is the one of dense multiple (acoustic, electromagnetic or elastic) scattering media. Computing waves in such media requires to take into account not only the interaction between the incident wave and the scatterers, but also the effects of the interactions between the scatterers themselves. When the number of scatterers is very large (and possibly for high frequency [37], [36]), specific deterministic or stochastic numerical methods and

algorithms are needed. We introduce new optimized numerical methods for solving such complex configurations. Many applications are related to this kind of problem like e.g. for osteoporosis diagnosis where quantitative ultrasound is a recent and promising technique to detect a risk of fracture. Therefore, numerical simulation of wave propagation in multiple scattering elastic medium in the high frequency regime is a very useful tool for this purpose.

4. Application Domains

4.1. Robotic swimmers

Some companies aim at building biomimetic robots that can swim in an aquarium, as toys (Robotswim) [1] but also for medical objectives. During the last three years, some members of the Inria Project-Team CORIDA [2] (Munnier, Scheid and Takahashi) together with members of the automatics laboratory of Nancy CRAN (Daafouz, Jungers) have initiated an active collaboration (CPER AOC) to construct a swimming ball in a very viscous fluid. This ball has a macroscopic size but since the fluid is highly viscous, its motion is similar to the motion of a nanorobot. Such nanorobots could be used for medical purposes to bring some medicine or perform small surgical operations. In order to get a better understanding of such robotic swimmers, we have obtained control results via shape changes and we have developed simulation tools (see [85], [84], [83]). However, in practice the admissible deformations of the ball are limited since they are realized using piezo-electric actuators. In the next four years, we will take into account these constraints by developing two approaches :

1. Solve the control problem by limiting the set of admissible deformations.
2. Find the "best" location of the actuators, in the sense of being the closest to the exact optimal control.

The main tools for this investigation are the 3D codes that we have developed for simulation of fish into a viscous incompressible fluid (`SUSHI3D`) or into a inviscid incompressible fluid (`SOLEIL`).

4.2. Aeronautics

We will develop robust and efficient solvers for problems arising in aeronautics (or aerospace) like electromagnetic compatibility and acoustic problems related to noise reduction in an aircraft. Our interest for these issues is motivated by our close contacts with companies like Airbus or "Thales Systèmes Aéroportés". We will propose new applications needed by these partners and assist them in integrating these new scientific developments in their home-made solvers. In particular, in collaboration with C. Geuzaine (Université de Liège), we are building a freely available parallel solver based on Domain Decomposition Methods that can handle complex engineering simulations, in terms of geometry, discretization methods as well as physics problems, see http://onelab.info/wiki/GetDDM. Part of this development is done through the grant ANR BECASIM.

5. Highlights of the Year

5.1. Highlights of the Year

The CANUM ("Congrès d'Analyse Numérique", Conference on Numerical Analysis) is the major French-speaking conference on numerical analysis and scientific computing. It is held since 1967 (every year from 1967 to 2000, every two years from 2000). In 2016, the Institut Élie Cartan de Lorraine was in charge of the organization. Most of the members of our team were involved throughout the year. In particular, Karim Ramdani was head of the organizing committee.

[1] The website http://www.robotic-fish.net/ presents a list of several robotic fish that have been built in the last years.
[2] Most members of SPHINX were members of the former Inria project-team CORIDA

6. New Software and Platforms

6.1. GPELab

Gross-Pitaevskii equations Matlab toolbox
KEYWORDS: 3D - Quantum chemistry - 2D
FUNCTIONAL DESCRIPTION

GPELab is a Matlab toolbox developed to help physicists compute ground states or dynamics of quantum systems modeled by Gross-Pitaevskii equations. This toolbox allows the user to define a large range of physical problems (1d-2d-3d equations, general nonlinearities, rotation term, multi-components problems...) and proposes numerical methods that are robust and efficient.

- Contact: Xavier Antoine
- URL: http://gpelab.math.cnrs.fr/

6.2. GetDDM

KEYWORDS: Large scale - 3D - Domain decomposition - Numerical solver
FUNCTIONAL DESCRIPTION

GetDDM combines GetDP and Gmsh to solve large scale finite element problems using optimized Schwarz domain decomposition methods.

- Contact: Xavier Antoine
- URL: http://onelab.info/wiki/GetDDM

6.3. μ-diff

μ-diff is a Matlab toolbox developed with B. Thierry (UPMC, France) for solving 2D multiple scattering problems by a random collection of circular cylinders.

- Contact: Xavier Antoine
- URL: http://mu-diff.math.cnrs.fr/mu-diff/

6.4. Platforms

6.4.1. A software for the efficient assignment of L-INP students

Each year, the 1500 students of the L-INP Collégium (gathering most of the engineering students in Lorraine) have to choose one or several among the 70+ courses. J-F. Scheid, a member of our team, is a faculty member of TELECOM Nancy and developed a solver giving a fair, fast and reliable assignment of the students to the courses. The solver works with integer linear optimization and is written in Python and CBC/COIN-OR.

7. New Results

7.1. Analysis, control and stabilization of heterogeneous systems

Participant: Takéo Takahashi.

In [12], T. Takahashi (with D. Maity and M. Tucsnak, both from Institut de Mathématiques de Bordeaux, France) has considered a free boundary problem modeling the motion of a piston in a viscous gas. The gas-piston system fills a cylinder with fixed extremities, which possibly allow gas from the exterior to penetrate inside the cylinder. The gas is modeled by the 1D compressible Navier-Stokes system and the piston motion is described by the second Newton law. They prove the existence and uniqueness of global in time strong solutions. The main novelty brought in is that the case of nonhomogeneous boundary conditions is considered. Moreover, even for homogeneous boundary conditions, their results require less regularity of the initial data than those obtained in previous works.

In [32], T. Takahashi (with C. Lacave from Institut Fourier, Grenoble, France) has studied the motion of a single disk moving under the influence of a 2D viscous fluid. They deal with the asymptotic as the size of the solid tends to zero. If the density of the solid is independent of the size of the solid, the energy equality is not sufficient to obtain a uniform estimate for the solid velocity. This will be achieved thanks to the optimal $L^p - L^q$ decay estimates of the semigroup associated to the fluid-rigid body system and to a fixed point argument. Next, they deduce the convergence to the solution of the Navier-Stokes equations in $\mathbb{R}^2$.

In [7], T. Takahashi (with C. Bianchini (Dimai, Florence, Italy) and A. Henrot (IECL, Nancy, France)) has tackled a model for the shape of vesicles. In order to do this, they consider a shape optimization problem associated with a Willmore type energy in the plane. More precisely, they study a *Blaschke-Santaló diagram* involving the area, the perimeter and the elastic energy of planar convex bodies. Existence, regularity and geometric properties of solutions to this shape optimization problem are shown.

We have studied the self-propelled motions of a rigid body immersed in a viscous incompressible fluid which fills the exterior domain of the rigid body. The mechanism used by the body to reach the desired motion is modeled through a distribution of velocities at its boundary.

T. Takahashi (with J. San Martín (DIM, Santiago, Chile) and M. Tucsnak (Institut de Mathématiques de Bordeaux, France)) considers in [16] a class of swimmers of low Reynolds number, of prolate spheroidal shape, which can be seen as simplified models of ciliated microorganisms. Within this model, the form of the swimmer does not change, the propelling mechanism consisting in tangential displacements of the material points of swimmer's boundary. Using explicit formulas for the solution of the Stokes equations at the exterior of a translating prolate spheroid the governing equations reduce to a system of ODE's with the control acting in some of its coefficients (bilinear control system). The main theoretical result asserts the exact controllability of the prolate spheroidal swimmer. In the same geometrical situation, they define a concept of efficiency which reduces to the classical one in the case of a spherical swimmer and they consider the optimal control problem of maximizing this efficiency during a stroke. Moreover, they analyse the sensitivity of this efficiency with respect to the eccentricity of the considered spheroid. They provide semi-explicit formulas for the Stokes equations at the exterior of a prolate spheroid, with an arbitrary tangential velocity imposed on the fluid-solid interface. Finally, they use numerical optimization tools to investigate the dependence of the efficiency on the number of inputs and on the eccentricity of the spheroid. The "best" numerical result obtained yields an efficiency of 30.66% with 13 scalar inputs. In the limiting case of a sphere their best numerically obtained efficiency is of 30.4%, whereas the best computed efficiency previously reported in the literature was of 22%.

In [10], T. Takahashi (with T. Hishida (Nagoya University, Japan) and A.L. Silvestre (IST, Lisboa, Portugal)) tackles the stationary case. The fluid motion is modeled by the stationary Navier-Stokes system coupled with two relations for the balance of forces and torques. They prove that there exists a control allowing the rigid body to move with a prescribed rigid velocity provided the velocity is small enough. They also show that since the net force exerted by the fluid to the rigid body vanishes, we have a better summability of the fluid velocity than the classical summability result for the solutions of the stationary Navier-Stokes system in exterior domains.

7.2. Inverse problems for heterogeneous systems

Participants: David Dos Santos Ferreira, Alexandre Munnier, Karim Ramdani, Julie Valein, Jean-Claude Vivalda.

Many inverse problems (IP) appearing in fluid-structure interaction and wave propagation problems have been investigated in the team.

In [14], Munnier and Ramdani consider the 2D inverse problem of recovering the positions and the velocities of slowly moving small rigid disks in a bounded cavity filled with a perfect fluid. Using an integral formulation, they first derive an asymptotic expansion of the DtN map of the problem as the diameters of the disks tend to zero. Then, combining a suitable choice of exponential type data and the DORT method (French acronym for Diagonalization of the Time Reversal Operator), a reconstruction method for the unknown positions and velocities is proposed. Let us emphasize here that this reconstruction method uses in the context of fluid-structure interaction problems a method which is usually used for waves inverse scattering (the DORT method).

In [13], Munnier and Ramdani propose a new method to tackle a geometric inverse problem related to Calderón's inverse problem. More precisely, they propose an explicit reconstruction formula for the cavity inverse problem using conformal mapping. This formula is derived by combining two ingredients: a new factorization result of the DtN map and the so-called generalized Pólia-Szegö tensors of the cavity.

In [9], P. Caro (Department of Mathematics and Statistics, Helsinki, Finland), D. Dos Santos Ferreira and Alberto Ruiz (Instituto de Ciencias Matematicas, Madrid, Spain) obtained stability estimates for potentials in a Schrödinger equation in dimension higher than 3 from the associated Dirichlet-to-Neumann map with partial data. The estimates are of log-log type and represent a quantitative version of the uniqueness result of Kenig, Sjöstrand and Uhlmann. The proof is based on a reduction to a stability estimate on the attenuated geodesic ray transform on the hypersphere.

In [15], Ramdani, Tucsnak (Institut de Mathématiques de Bordeaux, France) and Valein tackle a state estimation problem for a system of infinite dimension arising in population dynamics (a linear model for age-structured populations with spatial diffusion). Assume the initial state to be unknown, the considered inverse problem is to estimate asymptotically on time the state of the system from a locally distributed observation in both age and space. This is done by designing a Luenberger observer for the system, taking advantage of the particular spectral structure of the problem (the system has a finite number of unstable eigenvalues).

In [2], Ammar (Faculté des Sciences de Sfax, Tunisia), Massaoud (Faculté des Sciences de Sfax, Tunisia) and Vivalda characterize the globally Lipschitz continuous systems defined on $\mathbb{R}^n$ whose observability is preserved under time sampling.

7.3. Numerical analysis and simulation of heterogeneous systems

Participants: Xavier Antoine, Mohamed El Bouajaji, Karim Ramdani, Qinglin Tang, Julie Valein, Chi-Ting Wu.

In optics, metamaterials (also known as negative or left-handed materials), have known a growing interest in the last two decades. These artificial composite materials exhibit the property of having negative dielectric permittivity and magnetic permeability in a certain range of frequency, leading hence to materials with negative refractive index and super lens effects. In [8], Bunoiu (IECL, Metz, France) and Ramdani consider a complex wave system involving such materials. More precisely, they consider a periodic homogenization problem involving two isotropic materials with conductivities of different signs: a classical material and a metamaterial (or negative material). Combining the $\mathbf{T}-$coercivity approach and the unfolding method for homogenization, they prove well-posedness results for the initial and the homogenized problems and obtain a convergence result, provided that the contrast between the two conductivities is large enough (in modulus).

In [18], Tucsnak (Institut de Mathématiques de Bordeaux, France), Valein and Wu study the numerical approximation of the solutions of a class of abstract parabolic time-optimal control problems with unbounded control operator. Our main results assert that, provided that the target is a closed ball centered at the origin and of positive radius, the optimal time and the optimal controls of the approximate time optimal problems converge (in appropriate norms) to the optimal time and to the optimal controls of the original problem. In order to prove our main theorem, we provide a nonsmooth data error estimate for abstract parabolic systems.

In [4], Antoine and Lorin (School of Mathematics and Statistics, Ottawa, and CRM, Montréal, Canada) analyze the convergence of optimized Schwarz domain decomposition methods for the simulation of the time-domain Schrödinger equation with high-order local transmission conditions.

In [5], Antoine, Tang and Zhang (WPI, Austria and IRMAR, France) develop some spectral methods for computing the ground states and dynamics of space fractional Gross-Pitaevskii equations arising in the modeling of fractional Bose-Einstein equations with long-range nonlinear interactions. In addition, we also state some existence and uniqueness properties for the ground states of such equations, and prove some dynamical laws.

In [6], Bao (Department of Mathematics, Singapore), Tang and Zhang (WPI, Austria and IRMAR, France) develop a new efficient and spectrally accurate numerical for computing the ground state and dynamics of dipolar Bose-Einstein condensates. They pay a particular attention to the computation of the nonlinear nonlocal interactions through the use of the nonuniform fast Fourier transform.

In [22], Antoine, Levitt (CERMICS, France) and Tang derive a highly accurate and efficient new numerical method for computing the ground states of the fast rotating Gross-Pitaevskii equation. The method is based on a preconditioned nonlinear conjugate gradient method which leads to a high gain compared to most recent approaches.

In [26], Bao (Department of Mathematics, Singapore), Cai (Department of mathematics Purdue University, USA and CSRC, Beijing, China), Jia (Department of Mathematics, Singapore), Tang develop a uniformly accurate multiscale time integrator in conjunction with a spectral method for computing the dynamics of the nonrelativistic Dirac equation. The same authors develop and compare, in [27], some new numerical methods for the simulation of the Dirac equation when the nonrelativistic regime is considered.

The article [17] is devoted to explain how the open finite element solver GetDDM works. The mathematical methods behind GetDDM are optimized Schwarz domain decomposition methods with well-designed transmission boundary conditions. GetDDM allows to solve large scale high frequency wave problems (e.g. acoustics, electromagnetism, elasticity problems) on large clusters. This papers explains through examples and scripts how GetDDM must be used. GetDDM is a result of a long term collaboration between Xavier Antoine and Christophe Geuzaine (University of Liège).

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Grants with Industry

The Ph.D thesis of Boris Caudron is funded through a CIFRE contract with Thalès and a contract with the IECL. The goal of the Ph.D. thesis is to design new coupling techniques between integral equation methods and the finite element method for solving electromagnetic scattering problems. The advisors are Xavier Antoine (Sphinx) and Christophe Geuzaine (University of Liège).

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. ANR

- David Dos Santos Ferreira is the coordinator (PI) of a Young Researcher Program of the French National Research Agency (ANR) :
  Project Acronym : iproblems
  Project Title : Inverse Problems
  Coordinator : David Dos Santos Ferreira
  Duration : 48 months (2013-2017)

- Takéo Takahashi is the coordinator (PI) of a Researcher Program of the French National Research Agency (ANR) :
  Project Acronym : IFSMACS
  Project Title : Fluid-Structure Interaction: Modeling, Analysis, Control and Simulation
  Coordinator: Takéo Takahashi
  Duration : 48 months (starting on October 1st, 2016)
  URL: http://ifsmacs.iecl.univ-lorraine.fr/
- Xavier Antoine is member of the project TECSER funded by the French armament procurement agency in the framework of the Specific Support for Research Works and Innovation Defense (ASTRID 2013 program) operated by the French National Research Agency.
  Project Acronym: TECSER
  Project Title : Nouvelles techniques de résolution adaptées à la simulation haute performance pour le calcul SER
  Coordinator: Stéphane Lanteri (Inria, NACHOS project-team)
  Duration: 36 months (starting on May 1st, 2014)
  URL: http://www-sop.inria.fr/nachos/projects/tecser/index.php/Main/HomePage
- Xavier Antoine is member of the project BoND.
  Project Acronym: BoND
  Project Title: Boundaries, Numerics and Dispersion.
  Coordinator: Sylvie Benzoni (Institut Camille Jordan, Lyon, France)
  Duration: 48 months (starting on October 15th, 2013)
  URL: http://bond.math.cnrs.fr
- Xavier Antoine is the local coordinator of the ANR project BECASIM.
  Project acronym: BECASIM
  Project Title: Bose-Einstein Condensates: Advanced SIMulation Deterministic and Stochastic Computational Models, HPC Implementation, Simulation of Experiments.
  Coordinator: Ionut Danaila (Université de Rouen, France)
  Duration: 48 months (plus an extension of 12 months, until November 2017)
  URL: http://becasim.math.cnrs.fr

9.1.2. CNRS

Thomas Chambrion is the coordinator of the Research Project from CNRS Inphynity "DISQUO" (5300 euros, 2016).

9.2. International Initiatives

9.2.1. Participation in Other International Programs

Within the PHC Utique programme, a project of French-Tunisian collaboration involving some members of our team has been selected by Campus France. The exact amount of the budget is not known yet and will be comprised between 9000 and 16000 euros.

9.3. International Research Visitors

9.3.1. Visits to International Teams

Xavier ANTOINE has been a visitor of the Beijing CSRC for 4 weeks during the summer 2016.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General chair, scientific chair

Xavier Antoine was a member of the scientific committee of Waves 2017, University of Minneapolis, USA.

10.1.1.2. Member of the Organizing Committees

Several members of the team were involved in the organization of the 43rd national conference CANUM 2016 (http://smai.emath.fr/canum2016/). In particular, Karim Ramdani was the head of the Organizing Committee.

Xavier Antoine was co-organizer of Colloque Couplages numériques, hold in September 27-29, 2016, in Nice, France. http://math.unice.fr/~massonr/CouplagesNumeriques/index.php

Julie Valein organized a day Fédération Charles Hermite "Estimation for dynamical systems" (06/10/2016)

10.1.2. Scientific Events Selection

10.1.2.1. Reviewer

Thomas Chambrion is a reviewer for the American Control Conference and the Conference on Decision and Control.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

Jean-Claude Vivalda is a member of the editorial board of the *Journal of Dynamical and Control Systems*.

10.1.3.2. Reviewer - Reviewing Activities

Most of the members of our team are regular reviewer for major publications in the field of control.

- Thomas Chambrion is a reviewer for SICON, IEEE TAC, Automatica, International Journal of Control, MCMS.
- Julie Valein is a reviewer for SICON, ESAIM COCV.
- Jean-Claude Vivalda is a reviewer for SICON and for the Mathematical Reviews.

10.1.4. Invited Talks

Julie Valein was invited to

- LMV seminar, Versailles, 14 janvier 2016
- Mathematics-Automatic meeting, IECL – CRAN, Nancy, 28 June, 2016
- Conference « Stability of non-conservative systems », Valenciennes, 4-7 July 2016

Xavier Antoine was invited to

- Seminar, Bale University, December 2016.
- Seminar, Beijing University, July 2016.

10.1.5. Scientific Expertise

Julie Valein was a member of several "Comité de selection":

- for an associate professor position at École des Mines de Nancy;
- for an associate professor position at Université Lyon 1;
- for a teaching position at École des Sciences et Techniques de l'Ingénieur de Nancy.

Thomas Chambrion belongs to the selection panel for the Natural Sciences and Engineering Research Council of Canada.

10.1.6. Research Administration

- Xavier Antoine has been head of IECL since September 2015.
- David Dos Santos has been head of IECL PDE team since September 2014.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Most of the members of the team have a teaching position at Université de Lorraine.

Xavier Antoine teaches at Mines Nancy and ENSEM (Université de Lorraine), L3-M1, 96 hours.

Thomas Chambrion teaches at ESSTIN (Université de Lorraine), L1-L2, 192 hours.

David Dos Santos Ferreira teaches at UFR STMIA (Université de Lorraine), 192 hours.

Alexandre Munnier teaches at UFR STMIA (Université de Lorraine), 192 hours.

Jean-François Scheid teaches at Telecom Nancy (Université de Lorraine), 192 hours.

Julie Valein teaches at ESSTIN (Université de Lorraine), L1-L2, 192 hours.

10.2.2. Supervision

PhD in progress : Boris Caudron, CIFRE thesis with Thales, Coupling between integral equations/finite element for the numerical solution by domain decomposition methods of wave scattering problems, since June 2015, Xavier Antoine and Christophe Guezaine.

PhD in progress : Alessandro Duca, controllability of bilinear Schrödinger equations, since September 2015, Nabile Boussaïd and Thomas Chambrion.

10.2.3. Juries

Xavier Antoine was a referee for the Ph.D. thesis of P. Rammaciotti Morales (Ecole Polytechnique), and Marc Bakry (ENSTA).

Thomas Chambrion was referee of the PhD thesis of Leo Van Damme (Université de Bourgogne).

10.3. Popularization

Karim Ramdani has given several talks at Université de Lorraine to raise researchers awareness on the risks of author-pays publication model (for more information on economic models of scientific publishing, see http://iecl.univ-lorraine.fr/~Karim.Ramdani/KR_BIB/AUTEURS.html).

Thomas Chambrion gave a presentation of applied mathematics at Lycée Poincaré (Nancy) in April 2016.

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