Activity Report 2015

Team SPHINX

System with physical heterogenities : inverse problems, numerical simulation, control and stabilization

Inria teams are typically groups of researchers working on the definition of a common project, and objectives, with the goal to arrive at the creation of a project-team. Such project-teams may include other partners (universities or research institutions).

RESEARCH CENTER
Nancy - Grand Est

THEME
Optimization and control of dynamic systems

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Team SPHINX

Creation of the Team: 2015 January 01

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1. Members

Research Scientists

Takeo Takahashi [Team leader, Inria, Researcher, HdR]
Karim Ramdani [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]
Mohamed El Bouajaji [Univ. Lorraine]
Alexandre Munnier [Univ. Lorraine, Associate Professor]
Jean-François Scheid [Univ. Lorraine, Associate Professor, HdR]
Marius Tucsnak [Univ. Lorraine, Professor, HdR]
Julie Valein [Univ. Lorraine, Associate Professor]

PhD Students

Boris Caudron [Thales, from Jun 2015]
Chi-Ting Wu [Univ. Lorraine]

Post-Doctoral Fellow

Qinglin Tang [Univ. Lorraine]

Administrative Assistant

Celine Simon [Inria]

Other

Arthur Bottois [Inria,from Jun 2015 until Aug 2015]

2. Overall Objectives

2.1. Overall Objectives

In this project, we investigate theoretical and numerical issues concerning heterogeneous 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 fishes 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 heterogenous 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 require 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 [98], [90], [69], 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, [57], [58], [91]) or strong solutions for the case of a ball [95]. 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 [59], [45], [92]. 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 [48]). One can then solve the FSIS by considering the Navier-Stokes system with a penalization term taking into account the structure ([42], [89], [53]) or using a time discretization in order to fix the rigid body during some time interval ([63]). Using an appropriate change of variables has also been used (see [62], [94]), 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 large time behavior of this system and the existence of time periodic solutions [97], [79], [60].

Many other FSIS have been studied as well. Let us mention, for instance, **rigid bodies immersed in an incompressible perfect fluid** ([81], [66], [61]), **in a viscous compressible fluid** ([47], [35], [52], [36]), in a **viscous multipolar fluid** or in an **incompressible non-Newtonian fluid** ([54]). 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 [40], [35], [72]) or approximate the equations of linear elasticity by a finite dimensional system (see [49], [38]). For strong solutions, the coupling between hyperbolic-parabolic systems leads to seek solutions with high regularity. The only known results [43], [44] 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 ([87]). Although simplified, this model already contains many difficulties and allows starting 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 [67], [37]). The strategy of control is similar to the classical method for a fluid (without solid) (see, for instance, [55]) but with the tools developed in [94]. A first result of stabilization was obtained in [83] 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 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 infinite-dimensional dynamics 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 [68] or Kaltenbacher, Neubauer, and Scherzer [70]). 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 infinite dimensional systems 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 [29], [56], [64], [93] for the design feedback controllers), an input (for instance source inverse problems [26], [39], [50]) 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 ([41]), specific one dimensional techniques (like in [30]) or observer-based methods as in [77].

   In the last few years, we have developed observers to solve initial data inverse problems for a class of linear infinite dimensional systems 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 [76]) have been introduced in automatic control theory to estimate the state of a (finite dimensional) dynamical system 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 [80] and more recently the one by Trinh and Fernando [96] devoted to functional observers). The generalization of observers (also called estimators or filters in the stochastic framework) to infinite dimensional systems goes back to the seventies (see for instance Bensoussan [33] or Curtain and Zwart [46]) and the theory is definitely less developed than in the finite dimensional case. Using observers, we have proposed in [82], [65] 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 [32], [31].

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 heterogenous 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 softwares 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.

3.3.1. Scientific description

- **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: such a procedure allows 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. [86], [71], [88], [84], [85], [78]). 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 propose to contribute to building hybrid algebraic/analytical preconditioners and quasi-optimal Domain Decomposition Methods (DDM) [34], [51],[8] 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 [28], [27]), specific deterministic or stochastic numerical methods and algorithms are needed. We propose to 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 toys robots that can swim in an aquarium for entertainment purposes (Robotswim) [1] and 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 [75], [74], [73]). 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 fishes into a viscous incompressible fluid (`SUSHI3D`) or into a inviscid incompressible fluid (`SOLEIL`).

4.2. Aeronautics

We 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 develop new software 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 (in particular with the postdoc position).

5. Highlights of the Year

5.1. Highlights of the Year

In collaboration with Colin Guillarmou, Matti Lassas and Jérôme Le Rousseau, David Dos Santos Ferreira organized an IHP trimester on Inverse Problems hold in April-June 2015 (more than 100 participants).

6. New Software and Platforms

6.1. GPELab

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

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

GPELab is a Matlab toolbox developed to help physicists for computing 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. Platform: Vir'Volt

Vir'Volt is a prototype build in ESSTIN, an engineering school of Université de Lorraine, as part of a student project. The prototype enters low-consumption vehicle race, where the winner covers a given distance (depending upon the race, around 20 km) at a given average speed (around 25 km/h) with the lowest energy consumption. Thomas Chambrion has been in charge of the embedded automatic speed control of Vir'Volt for 6 years. In 2016, Vir'Volt will take part in the European Shell Eco Marathon organized in London. The sloping track (up to 5% uphill and 4% downhill) required a complete rebuild of the transmission parts. The proposed configuration has been obtained after intensive numerical simulations.

- Contact: Thomas Chambrion
- URL: http://www.ecomotionteam.org/blog/?page_id=3072

7. New Results

7.1. Analysis, control and stabilization of heterogeneous systems

Motivated by the collision problem for rigid bodies in a perfect fluid, Munnier and Ramdani investigated in [9] the asymptotics of a 2D Laplace Neumann problem in a domain with cusp. The small parameter involved in the problem is the distance between the solid and the cavity's bottom. Denoting by $\alpha > 0$ the tangency exponent at the contact point, the authors prove that the solid always reaches the cavity in finite time, but with a non zero velocity for $\alpha < 2$ (real shock case), and with null velocity for $\alpha \geqslant 2$ (smooth landing case). The proof is based on a suitable change of variables transforming the Laplace Neumann problem into a generalized Neumann problem set on a domain containing a horizontal rectangle whose length tends to infinity as the solid approached the cavity.

The paper [14] presents the first positive result on approximate controllability for bilinear Schrödinger equations in presence of mixed spectrum when the interaction term is unbounded.

In [15], Tucsnak, Valein and Wu study the numerical approximation of the solutions of a class of abstract parabolic time optimal control problems. The 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 to the optimal time and to the optimal controls of the original problem. This is based on a nonsmooth data error estimate for abstract parabolic systems.

A vesicle is an elastic membrane containing a liquid and surrounded by another liquid. Such a vesicle can be found in nature or it can be created in laboratory. They can store and/or transport substances. Modeling vesicles is also a first step in order to study and understand the behavior of more complex cells such as red cells. Their studies are important for many applications, in particular in biological and physiological subjects. Recent papers have been devoted to both experimental studies to the modeling and finally to the mathematical analysis of the obtained models. There are many different models to describe the motion of the membrane and one can for instance optimize the shape in order to minimize the elastic energy of the membrane. Such a problem is tackled in [4] in the 2D case and in [6] in the 3D case. In [4], the optimization is done among convex domains whereas in [6], the authors consider the problem of minimizing the total mean curvature in order to understand the differences between the Helfrich energy and the Willmore energy. Up to now, these models are considered without any fluid.

In [13], San Martin, Takahashi and Tucsnak consider a class of low Reynolds number swimmers, 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. They obtain the exact controllability of the prolate spheroidal swimmer and the existence of an optimal control problem (in the sense of the efficiency during a stroke). They also provide a method to compute an approximation of the efficiency by using explicit formulas for the Stokes system at the exterior of a prolate spheroid, with some particular tangential velocities at the fluid-solid interface. They analyze the sensitivity of this efficiency with respect to the eccentricity of the considered spheroid and show that for small positive eccentricity, the efficiency of a prolate spheroid is better than the efficiency of a sphere. 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.

7.2. Inverse problems for heterogeneous systems

In [7], David Dos Santos Ferreira *et al.* obtain global stability estimates for a potential in a Schrödinger equation on an open bounded set in dimension $n = 3$ from the Dirichlet-to-Neumann map with partial data. This improves previous results where local stability was proved : the region under control was the penumbra delimited by a source of light outside of the convex hull of the open set. These local estimates provided stability of log-log type corresponding to the uniqueness results in Calderón's inverse problem with partial data proved by Kenig, Sjöstrand and Uhlmann. The corresponding global estimates are proved in all dimensions higher than three. The estimates are based on the construction of solutions of the Schrödinger equation by complex geometrical optics developed in the anisotropic setting by Dos Santos Ferreira, Kenig, Salo and Uhlmann to solve the Calderón problem in certain admissible geometries.

In [20], David Dos Santos Ferreira *et al.* proved uniform L^p resolvent estimates for the stationary damped wave operator. Uniform L^p resolvent estimates for the Laplace operator on a compact smooth Riemannian manifold without boundary were first established by Shen on the Torus, then by Dos Santos Ferreira-Kenig-Salo for general compact manifolds and advanced further by Bourgain-Shao-Sogge-Yao. An alternative proof relying on the techniques of semiclassical Strichartz estimates allows to handle non-self-adjoint perturbations of the Laplacian and embeds very naturally in the semiclassical spectral analysis framework, and applies in the damped wave context.

In [10], Munnier and Ramdani considered 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 [24], Munnier and Ramdani proposed a new method to tackle a geometric inverse problem related to Calderón's inverse problem. More precisely, they proposed 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 Polia-Szegö tensors of the cavity.

In [11], Ramdani, Tucsnak and Valein tackled a state estimation problem for an infinite dimensional system 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 [12], San Martin, Schwindt and Takahashi consider the geometrical inverse problem consisting in recovering an unknown obstacle in a viscous incompressible fluid by measurements of the Cauchy force on the exterior boundary. They deal with the case where the fluid equations are the non stationary Stokes system and using the enclosure method, they can recover the convex hull of the obstacle and the distance from a point to the obstacle. With the same method, they can obtain the same result in the case of a linear fluid–structure system composed by a rigid body and a viscous incompressible fluid. They also tackle the corresponding nonlinear systems: the Navier–Stokes system and a fluid–structure system with free boundary. Using complex spherical waves, they obtain some partial information on the distance from a point to the obstacle.

7.3. Numerical analysis and simulation of heterogeneous systems

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 [5], Bunoiu and Ramdani studied 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).

Several results on domain decomposition were obtained in the frame of the collaboration of Xavier Antoine with the team of Christophe Geuzaine (Belgium). The paper [3] deals with a Schwarz-type solver for domain decomposition, the paper [8] proposes a Schwarz-type domain decomposition for high frequency electromagnetism equations, the paper [1] exposes how to use of GPELab to solve Gross-Pitaevskii equations.

The paper [2] deals with domain decomposition for nonlinear Schrödinger equations and the book chapter [16] is focused on the modeling of Bose-Einstein condensates.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Grants with Industry

In June 2015, Boris Caudron began a CIFRE thesis with Thales under the academic supervision of Xavier Antoine. The accompanying support contract, about 45 000 euros, will be signed in January 2016.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. ANR

- David Dos Santos Ferreira is the coordinator (PI) of a Young Researcher Programme of the French National Research Agency (ANR) :
Project Acronym : iproblems
Project Title : Inverse Problems
Duration : 48 months (2013-2017)
Abstract: Inverse problems is a field in full expansion as shown by the numerous resident programs hosted in the different research institutes throughout the world, several striking breakthroughs achieved in the recent years and the flow of PhD students attracted by the subject. Strong groups and schools have appeared in Finland, the United States and Japan. In spite of its history in Analysis and Partial differential equations (in particular in microlocal analysis and control theory, both fields having strong interactions with Inverse Problems), the emergence of an organised group of mathematicians interested in the theoretical aspects of inverse problems has not yet occured in France. The ambition of this proposal is to structure a core of analysts with a strong interest in this field, to help them investigate several central questions related to geometric and analytic inverse problems, and to favor interactions between them, as well as with foreign partners and experts in the field.
Inverse problems deal with the recovery of an unknown quantity, typically a coefficient in a partial differential equation, from knowledge of specific measurements, for instance the Cauchy data on the solutions of the given equation. They are motivated by applications to Physical Sciences but give rise to many interesting and challenging mathematical problems which lie at the crossroad of analysis (partial differential equations, harmonic and microlocal analysis, control theory, etc.) and geometry (Riemannian and Lorentzian geometries). This project mainly focuses on Caldero´n's inverse conductivity problem and other closely related geometric and analytic problems. In particular, it aims at investigating identifiability issues for anisotropic problems, but also in the case where only partial data is available, as well as stability issues for those problems. It will also consider injectivity problems on geodesic ray transforms.
- 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
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
Duration: 48 months (starting on october 15th, 2013)
URL: http://bond.math.cnrs.fr

9.2. International Initiatives

9.2.1. Informal International Partners

Most of the SPHINX members are involved in long term cooperation with international partners. The most important one at this time is our informal partnership with Université de Liège (Belgium). In particular, the recently released software program GetDDM, is based on the paper [25] co-authored by Xaver Antoine and Christophe Geuzaine.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific events organisation

10.1.1.1. General chair, scientific chair

Together with Colin Guillarmou, Matti Lassas and Jérôme Le Rousseau, David Dos Santos Ferreira organized an IHP trimester on Inverse Problems in April-June 2015 (more than 100 participants).

Takahashi and Tucsnak organized a workshop “Infinite dimensional systems in fluid mechanics and biology’, from December 7th to December 11th in the Guadeloupe Island.

10.1.2. Scientific events selection

10.1.2.1. Member of the conference program committees

- Xavier Antoine was a member of the program committee of Waves 2015, Germany, Karlsruhe, July 20-24, 2015.
- Thomas Chambrion is a member of the program committee of IFAC CPDE 2016.

10.1.2.2. Reviewer

- Thomas Chambrion is a regular reviewer for papers submitted to IEEE CDC (2 papers in 2015) and ACC (2 papers in 2015).
- David Dos Santos Ferreira has written reviews for papers submitted to Annales Scientifiques de l’École Normale Supérieure and Annales de l’Institut Fourier.

10.1.3. Journal

10.1.3.1. Member of the editorial boards

Xavier Antoine has been in charge of Numerical Analysis in the editorial board of “Mathématiques Appliquées pour le Master/SMAI” since 2014.

10.1.3.2. Reviewer - Reviewing activities

Most of the members are reviewer for major journals in the fields.

- Xavier Antoine is a referee for about 15 journal papers a year in “Journal of Computational Physics” and various SIAM journals.
- Thomas Chambrion is a regular referee for the journals “Automatica” and “IEEE Transactions on Automatic Control”.
- Julie Valein is a regular referee for the journals “Mathematical Control and Related Fields” and “Discrete and Continuous Dynamical Systems A”.

10.1.4. Invited talks

Thomas Chambrion was organizer and chairman of the invited minisymposium “Quantum Control” in the conference SIAM CT 2015, organized in Paris.

Xavier Antoine has given invited talks in the following scientific events

- Minisymposium ”Numerical Simulation of Quantum and Kinetic Problems”, ICCP9, Singapore, January 2015.
- Workshop "Mathematical physics for cold atoms", Grenoble, March 2015.
- Semaine d’Analyse Numérique de Besançon : ”XFEM, Nitsche FEM, FEM Adaptative, Conditions aux Limites Artificielles”, June 2015.
- ”Complex phenomena in optics: theory and experiments”, November 2015 Besançon,

David Dos Santos Ferreira has given talks in the following conferences:

- Applied Inverse Problems, Helsinki, May 2015.
- School on Fourier Integral Operators, Ouagadougou, Burkina Faso.

Alexandre Munnier has participated to the following workshops as an invited speaker:

- Waveguides: Asymptotic Methods and NumericalAanalysis, Naples, May 2015.
- Third Workshop "Probl'emes Inverses et Doamines Associés", Marseille, December 2015.

Karim Ramdani participated as an invited speaker to the following workshops and conferences:

- Workshop of GDRI ReaDiNet : "Reaction-Diffusion Systems Arising in Biology", (Nancy, December 16–17, 2015).
- Conference "Stability and Reconstruction issues in Inverse Problems" (IHP, Paris, June 29 — july 4, 2015).
- Workshop DELSyS : Observing and controlling complex dynamical systems (Grenoble, November 12–14, 2014).

Julie Valein gave an invited talk at "Workshop on control and inverse problems", Besançon, March 2015.

10.1.5. Scientific expertise

- Xavier Antoine was in charge of the ANR mathematics program until August 2015.
- Thomas Chambrion belongs to the selection panel for the Natural Sciences and Engineering Research Council of Canada.
- Julie Valein belongs to the ANR expert panel for ANR JCJC.

10.1.6. Research administration

Xavier Antoine has been head of IECL since September 2015.

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), 96 hours(délégation CNRS).
- 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, 96 hours (maternity leave).

10.2.2. Supervision

PhD in progress : Chi-Ting Wu, Contrôle en temps optimal pour quelques EDP réversibles en temps, since October 2012, Marius Tucsnak and Julie Valein.

PhD in progress : Boris Caudron, CIFRE thesis with Thales, since June 2015, Xavier Antoine.

10.2.3. Juries

- Xavier Antoine was referee of the PhD thesis of E. Veneros (Université de Genève, May 2015) and M. Lecouvez (Ecole Polytechnique, July 2015). He was also referee of the HDR of F. Triki (Université de Grenoble, December 2015).
- Karim Ramdani was member of the PhD committees of Camille Carvalho (Ecole Polytechnique, December 4th, 2015) and Simon Marmorat (Université Paris-Saclay, November 12th, 2015).

10.3. Popularization

Karim Ramdani is interested in economic models of scientific publishing. He has given several talks to raise awareness of researchers on the risks of author-pays publication model.

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