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Project-Team DEFI

Shape reconstruction and identification

IN COLLABORATION WITH: Centre de Mathématiques Appliquées (CMAP)

RESEARCH CENTER
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THEME
Numerical schemes and simulations

Table of contents

Project-Team DEFI

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Keywords:

Computer Science and Digital Science:

6\. - Modeling, simulation and control
6.1. - Mathematical Modeling
6.1.1. - Continuous Modeling (PDE, ODE)
6.2. - Scientific Computing, Numerical Analysis & Optimization
6.2.1. - Numerical analysis of PDE and ODE
6.2.6. - Optimization
6.3. - Computation-data interaction
6.3.1. - Inverse problems

Other Research Topics and Application Domains:

1.3.1. - Understanding and simulation of the brain and the nervous system
3.3.1. - Earth and subsoil
5.3. - Nanotechnology and Biotechnology

1. Members

Research Scientists

Houssem Haddar [Team leader, Inria, Senior Researcher, HdR]
Lucas Chesnel [Inria, Researcher]
Jing-Rebecca Li [Inria, Researcher, HdR]

Faculty Members

Grégoire Allaire [Ecole Polytechnique, Professor, HdR]
Olivier Pantz [Ecole Polytechnique, Professor, HdR]

PhD Students

Simona Schiavi [Inria]
Gabrielle Fournet [Inria, granted by ANR CIACM project]
Matteo Giacomini [Ecole Polytechnique]
Mohamed Lakhal [Ecole Polytechnique]
Thi Phong Nguyen [Inria, granted by ANR METAMATH- project]
Van Khieu Nguyen [Univ. Paris XI]
Bilel Charfi [Inria, from Mar 2015]
Mathieu Chamaillard [ENSTA]
Thibaud Mercier [CIFRE, until Jul 2015]
Tobias Rienmüller [UNIV étrangère, until Oct 2015]
Shixu Meng [Inria, until Aug 2015]
Helle Majander [UNIV étrangère, from Mar 2015]
Lorenzo Audibert [EDF, until Jul 2015]

Post-Doctoral Fellows

Federico Benvenuto [Inria, until Jul 2015, granted by OSEO]
Zixian Jiang [Inria, granted by OSEO]

Administrative Assistant

Jessica Gameiro [Inria]

Other

Guilherme Da Costa Sales [Inria, internship, from May 2015 until Aug 2015]

2. Overall Objectives

2.1. Overall Objectives

The research activity of our team is dedicated to the design, analysis and implementation of efficient numerical methods to solve inverse and shape/topological optimization problems in connection with acoustics, electromagnetism, elastodynamics, and diffusion.

Sought practical applications include radar and sonar applications, bio-medical imaging techniques, non-destructive testing, structural design, composite materials, and diffusion magnetic resonance imaging.

Roughly speaking, the model problem consists in determining information on, or optimizing the geometry (topology) and the physical properties of unknown targets from given constraints or measurements, for instance, measurements of diffracted waves or induced magnetic fields.

In general this kind of problems is non-linear. The inverse ones are also severely ill-posed and therefore require special attention from regularization point of view, and non-trivial adaptations of classical optimization methods.

Our scientific research interests are the following:

- Theoretical understanding and analysis of the forward and inverse mathematical models, including in particular the development of simplified models for adequate asymptotic configurations.
- The design of efficient numerical optimization/inversion methods which are quick and robust with respect to noise. Special attention will be paid to algorithms capable of treating large scale problems (e.g. 3-D problems) and/or suited for real-time imaging.
- Development of prototype softwares for specific applications or tutorial toolboxes.

During the last four years we were particularly interested in the development of the following themes that will be presented in details later.

- Qualitative methods for inverse scattering problems
- Iterative and Hybrid inversion methods
- Topological optimization methods
- Direct and inverse models for Diffusion MRI
- Asymptotic models and methods for waves and diffusion.

3. Research Program

3.1. Research Program

The research activity of our team is dedicated to the design, analysis and implementation of efficient numerical methods to solve inverse and shape/topological optimization problems in connection with wave imaging, structural design, non-destructive testing and medical imaging modalities. We are particularly interested in the development of fast methods that are suited for real-time applications and/or large scale problems. These goals require to work on both the physical and the mathematical models involved and indeed a solid expertise in related numerical algorithms.

This section intends to give a general overview of our research interests and themes. We choose to present them through the specific academic example of inverse scattering problems (from inhomogeneities), which is representative of foreseen developments on both inversion and (topological) optimization methods. The practical problem would be to identify an inclusion from measurements of diffracted waves that result from the interaction of the sought inclusion with some (incident) waves sent into the probed medium. Typical applications include biomedical imaging where using micro-waves one would like to probe the presence of pathological cells, or imaging of urban infrastructures where using ground penetrating radars (GPR) one is interested in finding the location of buried facilities such as pipelines or waste deposits. This kind of applications requires in particular fast and reliable algorithms.

By “imaging” we shall refer to the inverse problem where the concern is only the location and the shape of the inclusion, while “identification” may also indicate getting informations on the inclusion physical parameters.

Both problems (imaging and identification) are non linear and ill-posed (lack of stability with respect to measurements errors if some careful constrains are not added). Moreover, the unique determination of the geometry or the coefficients is not guaranteed in general if sufficient measurements are not available. As an example, in the case of anisotropic inclusions, one can show that an appropriate set of data uniquely determine the geometry but not the material properties.

These theoretical considerations (uniqueness, stability) are not only important in understanding the mathematical properties of the inverse problem, but also guide the choice of appropriate numerical strategies (which information can be stably reconstructed) and also the design of appropriate regularization techniques. Moreover, uniqueness proofs are in general constructive proofs, i.e. they implicitly contain a numerical algorithm to solve the inverse problem, hence their importance for practical applications. The sampling methods introduced below are one example of such algorithms.

A large part of our research activity is dedicated to numerical methods applied to the first type of inverse problems, where only the geometrical information is sought. In its general setting the inverse problem is very challenging and no method can provide a universal satisfactory solution to it (regarding the balance cost-precision-stability). This is why in the majority of the practically employed algorithms, some simplification of the underlying mathematical model is used, according to the specific configuration of the imaging experiment. The most popular ones are geometric optics (the Kirchhoff approximation) for high frequencies and weak scattering (the Born approximation) for small contrasts or small obstacles. They actually give full satisfaction for a wide range of applications as attested by the large success of existing imaging devices (radar, sonar, ultrasound, X-ray tomography, etc.), that rely on one of these approximations.

Generally speaking, the used simplifications result in a linearization of the inverse problem and therefore are usually valid only if the latter is weakly non-linear. The development of these simplified models and the improvement of their efficiency is still a very active research area. With that perspective we are particularly interested in deriving and studying higher order asymptotic models associated with small geometrical parameters such as: small obstacles, thin coatings, wires, periodic media, ... Higher order models usually introduce some non linearity in the inverse problem, but are in principle easier to handle from the numerical point of view than in the case of the exact model.

A larger part of our research activity is dedicated to algorithms that avoid the use of such approximations and that are efficient where classical approaches fail: i.e. roughly speaking when the non linearity of the inverse problem is sufficiently strong. This type of configuration is motivated by the applications mentioned below, and occurs as soon as the geometry of the unknown media generates non negligible multiple scattering effects (multiply-connected and closely spaces obstacles) or when the used frequency is in the so-called resonant region (wave-length comparable to the size of the sought medium). It is therefore much more difficult to deal with and requires new approaches. Our ideas to tackle this problem will be motivated and inspired by recent advances in shape and topological optimization methods and also the introduction of novel classes of imaging algorithms, so-called sampling methods.

The sampling methods are fast imaging solvers adapted to multi-static data (multiple receiver-transmitter pairs) at a fixed frequency. Even if they do not use any linearization the forward model, they rely on computing the solutions to a set of linear problems of small size, that can be performed in a completely parallel procedure. Our team has already a solid expertise in these methods applied to electromagnetic 3-D problems. The success of such approaches was their ability to provide a relatively quick algorithm for solving 3-D problems without any need for a priori knowledge on the physical parameters of the targets. These algorithms solve only the imaging problem, in the sense that only the geometrical information is provided.

Despite the large efforts already spent in the development of this type of methods, either from the algorithmic point of view or the theoretical one, numerous questions are still open. These attractive new algorithms also suffer from the lack of experimental validations, due to their relatively recent introduction. We also would like to invest on this side by developing collaborations with engineering research groups that have experimental facilities. From the practical point of view, the most potential limitation of sampling methods would be the need of a large amount of data to achieve a reasonable accuracy. On the other hand, optimization methods do not suffer from this constrain but they require good initial guess to ensure convergence and reduce the number of iterations. Therefore it seems natural to try to combine the two class of methods in order to calibrate the balance between cost and precision.

Among various shape optimization methods, the Level Set method seems to be particularly suited for such a coupling. First, because it shares similar mechanism as sampling methods: the geometry is captured as a level set of an “indicator function” computed on a cartesian grid. Second, because the two methods do not require any a priori knowledge on the topology of the sought geometry. Beyond the choice of a particular method, the main question would be to define in which way the coupling can be achieved. Obvious strategies consist in using one method to pre-process (initialization) or post-process (find the level set) the other. But one can also think of more elaborate ones, where for instance a sampling method can be used to optimize the choice of the incident wave at each iteration step.The latter point is closely related to the design of so called “focusing incident waves” (which are for instance the basis of applications of the time-reversal principle). In the frequency regime, these incident waves can be constructed from the eigenvalue decomposition of the data operator used by sampling methods. The theoretical and numerical investigations of these aspects are still not completely understood for electromagnetic or elastodynamic problems.

Other topological optimization methods, like the homogenization method or the topological gradient method, can also be used, each one provides particular advantages in specific configurations. It is evident that the development of these methods is very suited to inverse problems and provide substantial advantage compared to classical shape optimization methods based on boundary variation. Their applications to inverse problems has not been fully investigated. The efficiency of these optimization methods can also be increased for adequate asymptotic configurations. For instance small amplitude homogenization method can be used as an efficient relaxation method for the inverse problem in the presence of small contrasts. On the other hand, the topological gradient method has shown to perform well in localizing small inclusions with only one iteration.

A broader perspective would be the extension of the above mentioned techniques to time-dependent cases. Taking into account data in time domain is important for many practical applications, such as imaging in cluttered media, the design of absorbing coatings or also crash worthiness in the case of structural design.

For the identification problem, one would like to also have information on the physical properties of the targets. Of course optimization methods is a tool of choice for these problems. However, in some applications only a qualitative information is needed and obtaining it in a cheaper way can be performed using asymptotic theories combined with sampling methods. We also refer here to the use of so called transmission eigenvalues as qualitative indicators for non destructive testing of dielectrics.

We are also interested in parameter identification problems arising in diffusion-type problems. Our research here is mostly motivated by applications to the imaging of biological tissues with the technique of Diffusion Magnetic Resonance Imaging (DMRI). Roughly speaking DMRI gives a measure of the average distance travelled by water molecules in a certain medium and can give useful information on cellular structure and structural change when the medium is biological tissue. In particular, we would like to infer from DMRI measurements changes in the cellular volume fraction occurring upon various physiological or pathological conditions as well as the average cell size in the case of tumor imaging. The main challenges here are 1) correctly model measured signals using diffusive-type time-dependent PDEs 2) numerically handle the complexity of the tissues 3) use the first two to identify physically relevant parameters from measurements. For the last point we are particularly interested in constructing reduced models of the multiple-compartment Bloch-Torrey partial differential equation using homogenization methods.

4. Application Domains

4.1. Radar and GPR applications

Conventional radar imaging techniques (ISAR, GPR, etc.) use backscattering data to image targets. The commonly used inversion algorithms are mainly based on the use of weak scattering approximations such as the Born or Kirchhoff approximation leading to very simple linear models, but at the expense of ignoring multiple scattering and polarization effects. The success of such an approach is evident in the wide use of synthetic aperture radar techniques.

However, the use of backscattering data makes 3-D imaging a very challenging problem (it is not even well understood theoretically) and as pointed out by Brett Borden in the context of airborne radar: “In recent years it has become quite apparent that the problems associated with radar target identification efforts will not vanish with the development of more sensitive radar receivers or increased signal-to-noise levels. In addition it has (slowly) been realized that greater amounts of data - or even additional “kinds” of radar data, such as added polarization or greatly extended bandwidth - will all suffer from the same basic limitations affiliated with incorrect model assumptions. Moreover, in the face of these problems it is important to ask how (and if) the complications associated with radar based automatic target recognition can be surmounted.” This comment also applies to the more complex GPR problem.

Our research themes will incorporate the development, analysis and testing of several novel methods, such as sampling methods, level set methods or topological gradient methods, for ground penetrating radar application (imaging of urban infrastructures, landmines detection, underground waste deposits monitoring,) using multistatic data.

4.2. Biomedical imaging

Among emerging medical imaging techniques we are particularly interested in those using low to moderate frequency regimes. These include Microwave Tomography, Electrical Impedance Tomography and also the closely related Optical Tomography technique. They all have the advantage of being potentially safe and relatively cheap modalities and can also be used in complementarity with well established techniques such as X-ray computed tomography or Magnetic Resonance Imaging.

With these modalities tissues are differentiated and, consequentially can be imaged, based on differences in dielectric properties (some recent studies have proved that dielectric properties of biological tissues can be a strong indicator of the tissues functional and pathological conditions, for instance, tissue blood content, ischemia, infarction, hypoxia, malignancies, edema and others). The main challenge for these functionalities is to built a 3-D imaging algorithm capable of treating multi-static measurements to provide real-time images with highest (reasonably) expected resolutions and in a sufficiently robust way.

Another important biomedical application is brain imaging. We are for instance interested in the use of EEG and MEG techniques as complementary tools to MRI. They are applied for instance to localize epileptic centers or active zones (functional imaging). Here the problem is different and consists into performing passive imaging: the epileptic centers act as electrical sources and imaging is performed from measurements of induced currents. Incorporating the structure of the skull is primordial in improving the resolution of the imaging procedure. Doing this in a reasonably quick manner is still an active research area, and the use of asymptotic models would offer a promising solution to fix this issue.

4.3. Non destructive testing and parameter identification

One challenging problem in this vast area is the identification and imaging of defaults in anisotropic media. For instance this problem is of great importance in aeronautic constructions due to the growing use of composite materials. It also arises in applications linked with the evaluation of wood quality, like locating knots in timber in order to optimize timber-cutting in sawmills, or evaluating wood integrity before cutting trees. The anisotropy of the propagative media renders the analysis of diffracted waves more complex since one cannot only relies on the use of backscattered waves. Another difficulty comes from the fact that the micro-structure of the media is generally not well known a priori.

Our concern will be focused on the determination of qualitative information on the size of defaults and their physical properties rather than a complete imaging which for anisotropic media is in general impossible. For instance, in the case of homogeneous background, one can link the size of the inclusion and the index of refraction to the first eigenvalue of so-called interior transmission problem. These eigenvalues can be determined form the measured data and a rough localization of the default. Our goal is to extend this kind of idea to the cases where both the propagative media and the inclusion are anisotropic. The generalization to the case of cracks or screens has also to be investigated.

In the context of nuclear waste management many studies are conducted on the possibility of storing waste in a deep geological clay layer. To assess the reliability of such a storage without leakage it is necessary to have a precise knowledge of the porous media parameters (porosity, tortuosity, permeability, etc.). The large range of space and time scales involved in this process requires a high degree of precision as well as tight bounds on the uncertainties. Many physical experiments are conducted in situ which are designed for providing data for parameters identification. For example, the determination of the damaged zone (caused by excavation) around the repository area is of paramount importance since microcracks yield drastic changes in the permeability. Level set methods are a tool of choice for characterizing this damaged zone.

4.4. Diffusion MRI

In biological tissues, water is abundant and magnetic resonance imaging (MRI) exploits the magnetic property of the nucleus of the water proton. The imaging contrast (the variations in the grayscale in an image) in standard MRI can be from either proton density, T1 (spin-lattice) relaxation, or T2 (spin-spin) relaxation and the contrast in the image gives some information on the physiological properties of the biological tissue at different physical locations of the sample. The resolution of MRI is on the order of millimeters: the greyscale value shown in the imaging pixel represents the volume-averaged value taken over all the physical locations contained that pixel.

In diffusion MRI, the image contrast comes from a measure of the average distance the water molecules have moved (diffused) during a certain amount of time. The Pulsed Gradient Spin Echo (PGSE) sequence is a commonly used sequence of applied magnetic fields to encode the diffusion of water protons. The term 'pulsed' means that the magnetic fields are short in duration, an the term gradient means that the magnetic fields vary linearly in space along a particular direction. First, the water protons in tissue are labelled with nuclear spin at a precession frequency that varies as a function of the physical positions of the water molecules via the application of a pulsed (short in duration, lasting on the order of ten milliseconds) magnetic field. Because the precessing frequencies of the water molecules vary, the signal, which measures the aggregate phase of the water molecules, will be reduced due to phase cancellations. Some time (usually tens of milliseconds) after the first pulsed magnetic field, another pulsed magnetic field is applied to reverse the spins of the water molecules. The time between the applications of two pulsed magnetic fields is called the 'diffusion time'. If the water molecules have not moved during the diffusion time, the phase dispersion will be reversed, hence the signal loss will also be reversed, the signal is called refocused. However, if the molecules have moved during the diffusion time, the refocusing will be incomplete and the signal detected by the MRI scanner if weaker than if the water molecules have not moved. This lack of complete refocusing is called the signal attenuation and is the basis of the image contrast in DMRI. the pixels showning more signal attenuation is associated with further water displacement during the diffusion time, which may be linked to physiological factors, such as higher cell membrane permeability, larger cell sizes, higher extra-cellular volume fraction.

We model the nuclear magnetization of water protons in a sample due to diffusion-encoding magnetic fields by a multiple compartment Bloch-Torrey partial differential equation, which is a diffusive-type time-dependent PDE. The DMRI signal is the integral of the solution of the Bloch-Torrey PDE. In a homogeneous medium, the intrinsic diffusion coeffcient D will appear as the slope of the semi-log plot of the signal (in approporiate units). However, because during typical scanning times, 50-100ms, water molecules have had time to travel a diffusion distance which is long compared to the average size of the cells, the slope of the semi-log plot of the signal is in fact a measure of an 'effective' diffusion coefficient. In DMRI applications, this measured quantity is called the 'apparent diffusion coefficient' (ADC) and provides the most commonly used form the image contrast for DMRI. This ADC is closely related to the effective diffusion coefficient obtainable from mathematical homogenization theory.

5. New Software and Platforms

5.1. FVforBlochTorrey

FUNCTIONAL DESCRIPTION

We developed two numerical codes to solve the multiple-compartments Bloch-Torrey partial differential equation in 2D and 3D to simulate the water proton magnetization of a sample under the influence of diffusion-encoding magnetic field gradient pulses.

We coupled the spatial discretization with an efficient time discretization adapted to diffusive problems called the (explicit) Runge-Kutta-Chebyshev method.

The version of the code using Finite Volume discretization on a Cartesian grid is complete (written by Jing-Rebecca Li). The version of the code using linear Finite Elements discretization is complete (written by Dang Van Nguyen and Jing-Rebecca Li).

- Contact: Jing Rebecca Li
- URL: http://www.cmap.polytechnique.fr/~jingrebeccali/

5.2. InvGIBC

A FreeFem++ routines for solving inverse Maxwell's problem for 3D shape identification using a gradient descent method.

- Contact: Houssem Haddar
- URL: http://www.cmap.polytechnique.fr/~haddar/

5.3. RODIN

FUNCTIONAL DESCRIPTION

In the framework of the RODIN project we continue to develop with our software partner ESI the codes Topolev and Geolev for topology and geometry shape optimization of mechanical structures using the level set method.

- Contact: Grégoire Allaire
- URL: http://www.cmap.polytechnique.fr/~allaire/

5.4. samplings-2d

This software solves forward and inverse problems for the Helmholtz equation in 2-D.
FUNCTIONAL DESCRIPTION

This software is written in Fortran 90 and is related to forward and inverse problems for the Helmholtz equation in 2-D. It includes three independent components. The first one solves to scattering problem using integral equation approach and supports piecewise-constant dielectrics and obstacles with impedance boundary conditions. The second one contains various samplings methods to solve the inverse scattering problem (LSM, RGLSM(s), Factorization, MuSiC) for near-field or far-field setting. The third component is a set of post processing functionalities to visualize the results

- Contact: Houssem Haddar
- URL: http://sourceforge.net/projects/samplings-2d/

5.5. Samplings-3d

FUNCTIONAL DESCRIPTION

This software is written in Fortran 90 and is related to forward and inverse problems for the Helmholtz equation in 3-D. It contains equivalent functionalities to samplings-2d in a 3-D setting.

- Contact: Houssem Haddar
- URL: http://www.cmap.polytechnique.fr/~haddar/

6. New Results

6.1. Methods for inverse problems

6.1.1. Identifying defects in an unknown background using differential measurements

L. Audibert and H. Haddar

In the framework of the PhD thesis of Lorenzo Audibert we studied non destructive testing of concrete using ultrasonic waves, and more generallly imaging in complex heterogeneous media. We assume that measurements are multistatic, which means that we record the scattered field on different points by using several sources. For this type of data we wish to build methods that are able to image the obstacle that created the scattered field. We use qualitative methods in this work, which only provide the support of the object independently from its physical property. The first part of this thesis consists of a theoretical analysis of the Linear Sampling Method. Such analysis is done in the framework of regularization theory, and our main contribution is to provide and analyze a regularization term that ensures good theoretical properties. Among those properties we were able to demonstrate that when the regularization parameter goes to zero, we actually construct a sequence of functions that strongly converges to the solution of the interior transmission problem. This behavior gives a central place to the interior transmission problem as it allows describing the asymptotic solution of our regularized problem. Using this characterization of our solution, we are able to give the optimal reconstruction we can get from our method. More importantly this description of the solution allows us to compare the solution coming from two different datasets. Based on the result of this comparison, we manage to produce an image of the connected component that contains the defect which appears between two measurement campaigns and this regardless of the medium. This method is well suited for the characteristics of the microstructure of concrete as shown on several numerical examples with realistic concrete-like microstructure. Finally, we extend our theoretical results to the case of limited aperture, anisotropic medium and elastic waves, which correspond to the real physics of the ultrasounds

6.1.2. Invisibility in scattering theory for small obstacles

L. Chesnel, X. Claeys and S.A. Nazarov

We are interested in a time harmonic acoustic problem in a waveguide containing flies. The flies are modelled by small sound soft obstacles. We explain how they should arrange to become invisible to an observer sending waves from $-\infty$ and measuring the resulting scattered field at the same position. We assume that the flies can control their position and/or their size. On the other hand, we show that any sound soft obstacle (non necessarily small) embedded in the waveguide always produces some non exponentially decaying scattered field at $+\infty$. As a consequence, the flies cannot be made completely invisible to an observer equipped with a measurement device located at $+\infty$.

6.1.3. New notion of regularization for Poisson data with an application to nanoparticle volume determination

F. Benvenuto, H. Haddar and B. Lantz

The aim of this work is to develop a fully automatic method for the reconstruction of the volume distribution of diluted polydisperse non-interacting nanoparticles with identical shapes from Small Angle X-ray Scattering measurements. The described method solves a maximum likelihood problem with a positivity constraint on the solution by means of an Expectation Maximization iterative scheme coupled with a robust stopping criterion. We prove that this is a regularization method according to an innovative notion of regularization specifically defined for inverse problems with Poisson data. Such a regularization, together with the positivity constraint results in high fidelity quantitative reconstructions of particle volume distributions making the method particularly effective in real applications. We test the performance of the method on synthetic data in the case of uni- and bi-modal particle volume distributions. Moreover, we show the reliability of the method on real data provided by a Xenocs device prototype.

6.1.4. A conformal mapping algorithm for the Bernoulli free boundary value problem

H. Haddar and R. Kress

We propose a new numerical method for the solution of Bernoulli's free boundary value problem for harmonic functions in a doubly connected domain D in R^2 where an unknown free boundary Γ_0 is determined by prescribed Cauchy data on Γ_0 in addition to a Dirichlet condition on the known boundary Γ_1. Our main idea is to involve the conformal mapping method as proposed and analyzed by Akduman, Haddar and Kress for the solution of a related inverse boundary value problem. For this we interpret the free boundary Γ_0 as the unknown boundary in the inverse problem to construct Γ_0 from the Dirichlet condition on Γ_0 and Cauchy data on the known boundary Γ_1. Our method for the Bernoulli problem iterates on the missing normal derivative on Γ_1 by alternating between the application of the conformal mapping method for the inverse problem and solving a mixed Dirichlet–Neumann boundary value problem in D. We present the mathematical foundations of our algorithm and prove a convergence result. Some numerical examples will serve as proof of concept of our approach.

6.1.5. Identification of small objects with near-field data in quasi-backscattering configurations

H. Haddar and M. Lakhal

We present a new sampling method for detecting targets (small inclusions or defects) immersed in a homogeneous medium in three-dimensional space, from measurements of acoustic scattered fields created by point source incident waves. We consider the harmonic regime and a data setting that corresponds with quasi-backscattering configuration: the data is collected by a set a receivers that are distributed on a segment centered at the source position and the device is swept along a path orthogonal to the receiver line. We assume that the aperture of the receivers is small compared with the distance to the targets. Considering the asymptotic form of the scattered field as the size of the targets goes to zero and the small aperture approximation, one is able to derive a special expression for the scattered field. In this expression a separation of the dependence of scattered field on the source location and the distance source-target is performed. This allows us to propose a sampling procedure that characterizes the targets location in terms of the range of a near-field operator constructed from available data. Our procedure is similar to the one proposed by Haddar-Rezac for far-field configurations. The reconstruction algorithm is based on the MUSIC (Multiple SIgnal Classification) algorithm.

6.2. Direct scattering problems

6.2.1. A numerical method to approximate black hole singularities in presence of metamaterials

L. Chesnel, A.-S. Bonnet-Ben Dhia, C. Carvalho and P. Ciarlet.

We investigate in a 2D setting the scattering of time-harmonic electromagnetic waves by a plasmonic device, represented as a non dissipative bounded and penetrable obstacle with a negative permittivity. Using the T-coercivity approach, we proved that the problem is well-posed in the classical frameworks if the negative permittivity does not lie in some critical interval whose definition depends on the shape of the device. When the latter has corners, for values inside the critical interval, unusual strong singularities for the electromagnetic field can appear. In that case, well-posedness is obtained by imposing a radiation condition at the corners to select the outgoing black-hole plasmonic wave, that is the one which carries energy towards the corners. We give a simple and systematic criterion to define what is the outgoing solution. We also propose an original numerical method based on the use of Perfectly Matched Layers at the corners. We emphasize that it is necessary to design an *ad hoc* technique because the field is too singular to be captured with standard finite element methods.

6.2.2. Boundary Integral Equations for the Transmission Eigenvalue Problem for Maxwell's Equations

Houssem Haddar, Shixu Meng and Fioralba Cakoni

We consider the transmission eigenvalue problem for Maxwell's equations corresponding to non-magnetic inhomogeneities with contrast in electric permittivity that changes sign inside its support. We formulate the transmission eigenvalue problem as an equivalent homogeneous system of boundary integral equa- tion, and assuming that the contrast is constant near the boundary of the support of the inhomogeneity, we prove that the operator associated with this system is Fredholm of index zero and depends analytically on the wave number. Then we show the existence of wave numbers that are not transmission eigenvalues which by an application of the analytic Fredholm theory implies that the set of transmission eigenvalues is discrete with positive infinity as the only accumulation point.

6.2.3. A Volume integral method for solving scattering problems from locally perturbed periodic layers

Houssem Haddar and Thi Phong Nguyen

We investigate the scattering problem for the case of locally perturbed periodic layer in R^N $(N = 2, 3)$. Using Floquet-Bloch transform in x_1-direction we reformulate this scattering problem as an equivalent system of coupled volume integral equations. Using periodization in the x_2-direction we apply a spectral method to discretize the problem and compute a numerical approximation of the solution. The convergence of this method is established and numerical validating results are conducted.

6.3. Shape and topology optimization

6.3.1. Deterministic approximation methods in shape optimization under random uncertainties

G. Allaire and C. Dapogny

This work is concerned with the treatment of uncertainties in shape optimization. We consider uncertainties in the loadings, the material properties, the geometry and the vibration frequency, both in the parametric and geometric optimization setting. We minimize objective functions which are mean values, variances or failure probabilities of standard cost functions under random uncertainties. By assuming that the uncertainties are small and generated by a finite number N of random variables, and using first- or second-order Taylor expansions, we propose a deterministic approach to optimize approximate objective functions. The computational cost is similar to that of a multiple load problems where the number of loads is N. We demonstrate the effectiveness of our approach on various parametric and geometric optimization problems in two space dimensions.

6.3.2. Molding direction constraints in structural optimization via a level-set method

G. Allaire, F. Jouve and G. Michailidis

In the framework of structural optimization via a level-set method, we develop an approach to handle the directional molding constraint for cast parts. A novel molding condition is formulated and a penalization method is used to enforce the constraint. A first advantage of our new approach is that it does not require to start from a feasible initialization, but it guarantees the convergence to a castable shape. A second advantage is that our approach can incorporate thickness constraints too. We do not adress the optimization of the casting system, which is considered a priori defined. We show several 3d examples of compliance minimization in linearized elasticity under molding and minimal or maximal thickness constraints. We also compare our results with formulations already existing in the literature.

6.3.3. Identification of magnetic deposits in 2-D axisymmetric eddy current models via shape optimization

Zixian Jiang, Houssem Haddar, Armin Lechleiter and Mabrouka El-Guedri

The non-destructive control of steam generators is an essential task for the safe and failure-free operation of nuclear power plants. Due to magnetite particles in the cooling water of the plants, a frequent source for failures are magnetic deposits in the cooling loop of steam generators. From eddy current signals measured inside a U-tube in the steam generator, we propose and analyze a regularized shape optimization algorithm to identify magnetic deposits outside the U-tube with either known or unknown physical properties. Motivated by the cylindrical geometry of the U-tubes we assume an axisymmetric problem setting, reducing Maxwell's equations to a 2-D elliptic eddy current problem. The feasibility of the proposed algorithms is illustrated via numerical examples demonstrating in particular the stability of the method with respect to noise.

6.4. Asymptotic Analysis

6.4.1. Ion transport through deformable porous media: derivation of the macroscopic equations using upscaling

G. Allaire, O. Bernard, J.-F. Dufrêche and A. Mikelic

We study the homogenization (or upscaling) of the transport of a multicomponent electrolyte in a dilute Newtonian solvent through a deformable porous medium. The pore scale interaction between the flow and the structure deformation is taken into account. After a careful adimensionalization process, we first consider so-called equilibrium solutions, in the absence of external forces, for which the velocity and diffusive fluxes vanish and the electrostatic potential is the solution of a Poisson-Boltzmann equation. When the motion is governed by a small static electric field and small hydrodynamic and elastic forces, we use O'Brien's argument to deduce a linearized model. Then we perform the homogenization of these linearized equations for a suitable choice of time scale. It turns out that the deformation of the porous medium is weakly coupled to the electrokinetics system in the sense that it does not influence electrokinetics although the latter one yields an osmotic pressure term in the mechanical equations. As a consequence, the effective tensor satisfies Onsager properties, namely is symmetric positive definite.

6.4.2. On the asymptotic behaviour of the kernel of an adjoint convection-diffusion operator in a long cylinder

G. Allaire and A. Piatnitski

This work studies the asymptotic behaviour of the principal eigenfunction of the adjoint Neumann problem for a convection diffusion operator defined in a long cylinder. The operator coefficients are 1-periodic in the longitudinal variable. Depending on the sign of the so-called longitudinal drift (a weighted average of the coefficients), we prove that this principal eigenfunction is equal to the product of a specified periodic function and of an exponential, up to the addition of fast decaying boundary layer terms.

6.4.3. A comparison between two-scale asymptotic expansions and Bloch wave expansions for the homogenization of periodic structures

G. Allaire, M. Briane and M. Vanninathan

In this work we make a comparison between the two-scale asymptotic expansion method for periodic homogenization and the so-called Bloch wave method. It is well-known that the homogenized tensor coincides with the Hessian matrix of the first Bloch eigenvalue when the Bloch parameter vanishes. In the context of the two-scale asymptotic expansion method, there is the notion of high order homogenized equation where the homogenized equation can be improved by adding small additionnal higher order differential terms. The next non-zero high order term is a fourth-order term, accounting for dispersion effects. Surprisingly, this homogenized fourth-order tensor is not equal to the fourth-order tensor arising in the Taylor expansion of the first Bloch eigenvalue, which is often called Burnett tensor. Here, we establish an exact relation between the homogenized fourth-order tensor and the Burnett fourth-order tensor. It was proved by Conca et al. that the Burnett fourth-order tensor has a sign. For the special case of a simple laminate we prove that the homogenized fourth-order tensor may change sign. In the elliptic case we explain the difference between the homogenized and Burnett fourth-order tensors by a difference in the source term which features an additional corrector term. Finally, for the wave equation, the two fourth-order tensors coincide again, so dispersion is unambiguously defined, and only the source terms differ as in the elliptic case.

6.4.4. Influence of the geometry on plasmonic waves

L. Chesnel, X. Claeys and S.A. Nazarov
In the modeling of plasmonic technologies in time harmonic regime, one is led to study the eigenvalue problem $-\mathrm{div}(\sigma\nabla u) = \lambda u\ (P)$, where σ is a physical coefficient positive in some region Ω_+ and negative in some other region Ω_-. We highlight an unusual instability phenomenon for the source term problem associated with (P): for certain configurations, when the interface between Ω_+ and Ω_- presents a rounded corner, the solution may depend critically on the value of the rounding parameter. We explain this property studying the eigenvalue problem (P). We provide an asymptotic expansion of the eigenvalues and prove error estimates. We establish an oscillatory behaviour of the eigenvalues as the rounding parameter of the corner tends to zero. These theoretical results are illustrated by numerical experiments.

6.4.5. Effective boundary conditions for thin periodic coatings Participants

Mathieu Chamaillard, Houssem Haddar and Patrick Joly

We study the derivation of asymptotic model (generalized impedance boundary conditions) for periodic coating in 3-D configurations. The definition of periodicity for $3D$ surfaces cannot be done in an intrinsic way in general. We propose a definition based on the use of local parametrisations of the surface. This parametrization-dependent definition is somehow inspired from practical considerations in the manufacturing of periodic coatings. The asymptoic of the problem is constructed for the scalar problem and also for the electormagnetic problem. Approximate models of order 1 and 2 are derived for the scalar problem and are validated numerically. In the electromagnetic case, only conditions or order 1 are exhibited in the genral case.

6.5. Diffusion MRI

Jing-RebeccaLi, HoussemHaddar, SimonaSchiavi ,Khieu VanNguyen,GabrielleFournet

Diffusion Magnetic Resonance Imaging (DMRI) is a promising tool to obtain useful information on microscopic structure and has been extensively applied to biological tissues.

We obtained the following results.

- We derived using homogenization techniques a model of the time-dependent “apparent diffusion coefficient”(ADC) that is valid at a wide range of diffusion times. The ADC is a very important experimental quantity measured by diffusion MRI in biological tissues. This work resulted in one submitted article to a mathematical journal and we are preparing an article for a physics journal.

- We analyzed a dMRI model called the Karger model that is valid at long diffusion times. This resulted in one submitted article to a mathematical journal.
- We acquired dMRI data of the nerve cells of the Aplysia Californica at the high field brain MRI center Neurospin. This data is useful because the nerve cells are bigger than mammal neurons and so it is easier to obtain segmented geometrical information about these cells for model validation.
- We participated in the data analysis and numerical simulation of a MR imaging method to measure blood flow in micro-vessels in the brain. This resulted in a submitted article to a MRI journal.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

- Contract with EDF R&D on non destructive testing of concrete materials (in the framework of the PhD thesis of Lorenzo Audibert, defended in 2015)
- Contract with EDF R&D on data assimilation for temprature estimates in nuclear reactors (in the framework of the PhD thesis of Thibault Mercier, defended in 2015)
- A CIFRE PhD thesis started in January 2015 with Dassault Aviations. The student is M. Aloïs Bissuel who is working on "linearized Navier-Stokes equations for optimization, fluttering and aeroacoustic".
- A CIFRE PhD thesis started in December 2015 with Safran Tech. The student is Mrs Perle Geoffroy who is working on "topology optimization by the homogenization method in the context of additive manufacturing".

7.2. Bilateral Grants with Industry

- The RODIN projet finished in September 2015. RODIN is the acronym of "Robust structural Optimization for Design in INdustry". This is a consortium of various companies and universities which has been sponsored by the FUI AAP 13 for 3 years, starting on July 2012. The industrial partners are: Renault, EADS, ESI, Eurodecision, Alneos, DPS. The academic partners are: CMAP at Ecole Polytechnique, Laboratoire J.-L. Lions at Paris 6 and 7 Universities, centre de recherches Bordeaux Sud-Ouest at Inria. The goal of the RODIN project is to perform research and develop a computer code on geometry and topology optimization of solid structures, based on the level set method. The software editor ESI is going to isse a commercial software in 2016. A sequel for RODIN is planned with a possible start in 2016.
- FUI project Nanolytix. This three years project started in October 2012 and involves Xenocs (coordinator), imXPAD, Arkema, Inria (DEFI) and CEA-Leti. It aims at building a compact and easy-to use device that images nonaparticles using X-ray diffraction at small or wide angles (SAXS and WAXS technologies). We are in charge of direct and inverse simulation of the SAXS and WAXS experiments.
- Electormagnetic simulation work package of the FUI project Tandem. This three years project started in December 2012 and involves Bull-Amesys (coordinator), BOWEN (ERTE+SART), Ecole Polytechnique (CMAP), Inria, LEAT et VSM. It aims at constructing a radar system on a flying device capable of real-time imaging mines embedded in dry soils (up to 40 cm deep). We are in charge of numerical validation of the inverse simulator.
- FUI project Saxsize. This three years project started in October 2015 and involves Xenocs (coordinator), Inria (DEFI), Pyxalis, Cordouan and CEA. It is a followup of Saxsise where a focus is put on SAXS imaging of nanoparticles powders.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR

- H. Haddar is the DEFI coordinator of the ANR: Modelization and numerical simulation of wave propagation in metamaterials (METAMATH), program MN, 2011-2015. This is a joint ANR with POEMS, Inria Scalay Ile de France project team (Coordinator, S. Fliss), DMIA, Département de Mathématiques de l'ISAE and IMATH, Laboratoire de Mathématiques de l'Université de Toulon. https://www.rocq.inria.fr/poems/metamath
- J.R. Li is the coordinator of the Inria partner of the project "Computational Imaging of the Aging Cerebral Microvasculature", funded by ANR Program "US-French Collaboration". French Partners (Coordinating partner CEA Neurospin): CEA Neurospin (Coordinator Luisa Ciobanu), Inria Saclay (Coordinator Jing-Rebecca Li). US Partner: Univ of Illinois, bioengineering department (Coordinator Brad Sutton). Duration: Sept 2013- Sept 2016.

8.2. European Initiatives

8.2.1. Collaborations with Major European Organizations

- Partner 1: University of Bremen, Department of Math. (Germany)

  Joint PhD advising of T. Rienmuller, partly funded by French-German university. Correspondant: Armin Lechleiter.
- Partner 2: University of Goettingen, Department of Math. (Germany)

  Development of conformal mapping method to electrostatic inverse problems. Correspondant: Rainer Kress.

8.3. International Initiatives

8.3.1. Inria International Labs

- DEFI is the correpondnat of the LIRIMA Afrique team EPIC. The program ended in 2015. A followup is prepared in the framework of associate team program.

8.3.2. Inria International Partners

8.3.2.1. Declared Inria International Partners

QUASI

- Title: Qualitative Approaches to Scattering and Imaging
- International Partners (Institution - Laboratory - Researcher):
  - University of Delaware (United States) - Department of Mathematical Sciences (Department of Math) - Fioralba Cakoni
- Start year: 2013
- We concentrate on the use of qualitative methods in acoustic and electromagnetic inverse scattering theory with applications to nondestructive evaluation of materials and medical imaging. In particular, we address theoretical and numerical reconstruction techniques to solve the inverse scattering problems using either time harmonic or time dependent measurements of the scattered field. The main goal of research in this field is to not only detect but also identify geometric and physical properties of unknown objects in real time.

8.4. International Research Visitors

8.4.1. Visits of International Scientists

We had short visits (one week) of the following collaborators

- Fioralba Cakoni
- David Colton
- Ozgur Ozdemir
- Rainer Kress

8.4.1.1. Internships

- Guilherme Da Costa Sales
- Hoang Trong An TRAN

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific events organisation

- H. Haddar organized with A. Lechleiter the second edition of the Franco-German Summer School Inverse Problems for Waves Ecole Polytechnique, August 24-28, 2015. Over 50 partcipants took part of this event. This event was mainly funded by the Franco-German university with participation of Inria, Ecole polytechnique and University of Bremen. http://www.math.uni-bremen.de/zetem/cms/detail.php?template=ipschool2015_parse_title&person=ip-school2015

9.1.1.1. General chair, scientific chair

- G. Allaire is the scientific chair and one of the main organizers of the CEA/GAMNI seminar on computational fluid mechanics, IHP Paris (January 2015).

9.1.1.2. Member of the organizing committees

- G. Allaire, PGMO conference (27-28 October 2015).

9.1.2. Scientific events selection

9.1.2.1. Member of the conference program committees

- H. Haddar, Waves 2015, Kalsruhe (July 2015)

9.1.3. Journal

9.1.3.1. Member of the editorial boards

- G. Allaire is member of the editorial board of
  - book series "Mathématiques et Applications" of SMAI and Springer,
  - ESAIM/COCV, Structural and Multidisciplinary Optimization,
  - Discrete and Continuous Dynamical Systems Series B,
  - Computational and Applied Mathematics,
  - Mathematical Models and Methods in Applied Sciences (M3AS),
  - Annali dell'Universita di Ferrara,
  - OGST (Oil and Gas Science and Technology),
  - Journal de l'Ecole Polytechnique - Mathématiques,
  - Journal of Optimization Theory and Applications.
- H. Haddar is member of the editorial advisory board of Inverse Problems
- J.-R. Li is an Associate Editor of the SIAM Journal on Scientific Computing.

9.1.3.2. Reviewer - Reviewing activities

The members of the team reviewed numerous papers for numerous international journals. Too many to make a list.

9.1.4. Invited talks

- Lucas Chesnel gave a talk at the “Séminaire de Mathématiques Appliquées du Collège de France”. The video is available here http://www.college-de-france.fr/site/pierre-louis-lions/seminar-2015-01-16-11h15.htm
- Grégoire Allaire
  - 4ème conférence internationale de la SM2A, Oujda, Maroc (february 2015). Congrès "Simulation" de la Société des Ingénieurs de l’Automobile (SIA), Montigny le Bretonneux (march 2015).
  - Journées du GDR Mascot-Num, Saint-Etienne (april 2015).
  - European forum on additive manufacturing, Chatenay Malabry (june 2015).
  - Ecole d’été du CIMPA, Mumbai (july 2015).
  - Variational Analysis and Aerospace Engineering, Erice (september 2015).
  - Workshop on Optimal Control of Partial and Ordinary Differential Equations, Palaiseau (november 2015).
  - Calculus of Variations and its Applications, Lisboa (december 2015).
- Houssem Haddar
  - Mini-symposium “Inverse problems for elliptic PDEs, analysis and applications”, IFIP, June 29 - July 3, 2015
  - IMA Hot Topics Workshop, Hydraulic Fracturing: From Modeling and Simulation to Reconstruction and Characterization, University of Minnesota, May 11-14, 2015
  - Workshop "reconstruction, stability and applications in inverse problems", IHP, 29 June - 3 July 2015
  - Workshop “problèmes inverses pour les EDP”, Université de Reims, 2-3 June, 2015
  - Workshop on "Inverse Problems in Wave Propagation", IWaP 2015, University of Bremen, April 7-10, 2015.
  - Workshop on “Multi-scale Waveform Modeling and Inversion” at KAUST from March 22-24 2015

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

- Licence : Grégoire Allaire, Approximation Numérique et Optimisation, for students in the second year of Ecole Polytechnique curriculum: 8 lessons of 1h30.
- Licence : Houssem Haddar, Approximation Numérique et Optimisation, for students in the second year of Ecole Polytechnique curriculum: 8 TDs of 4h.
- Licence : Houssem Haddar, Variational analysis of partial differential equations, for students in the second year of Ecole Polytechnique curriculum: 8 TDs of 4h.
- Licence: Lucas Chesnel, “Elementary tools of analysis for partial differential equations”, 29 equivalent TD hours, L3, Ensta ParisTech, Palaiseau, France
- Licence: Lucas Chesnel, Mentoring for the course “Variational analysis of partial differential equations”, 15 equivalent TD hours, L3, École Polytechnique, Palaiseau, France
- Master : Grégoire Allaire, Optimal design of structures, for students in the third year of Ecole Polytechnique curriculum. 9 lessons of 1h30.
- Master : Grégoire Allaire, Transport et Diffusion, for students in the third year of Ecole Polytechnique curriculum. With F. Golse, 1/2 of 9 lessons of 1h30.

- Master : Grégoire Allaire, Functional analysis and applications, for Master (M2) students of Ecole Polytechnique and Paris 6 University, 6 lessons of 3h.
- Master : Houssem Haddar, Inverse problems, for Master (M2) students of Ecole Polytechnique and Paris 6 University, 1/2 of 9 lessons of 2h.
- Master: Lucas Chesnel, “A mathematical study of transmission problems with sign-changing coefficients”, (main instructor) 16 equivalent TD hours, M2, Ensta ParisTech, Palaiseau, France

9.2.2. Supervision

- Ph.D. : L. Audibert, Qualitative methods for non destructive testing of concrete like materials, September 2015, Ecole polytechnique, H. Haddar.
- Ph.D. : T. Mercier Data assimilation for temperature estimates in PWR, September 2015, Ecole polytechnique, H. Haddar.
- Ph.D. : T. Rienmuller, Scattering for inhomogeneous waveguides, 2015, September 2015 University of Bremen and Ecole polytechnique, A. Lechleiter and H. Haddar.
- Ph.D. in progress: M. Lakhal, Time domain inverse scattering for buried objects, 2014, H. Haddar
- Ph.D. in progress: T.P. Nguyen, Direct and Inverse scattering from locally perturbed layers, 2013, H. Haddar
- Ph.D. in progress: B. Charfi, Identification of the sigular support of a GIBC, 2014, H. Haddar and S. Chaabane
- Ph.D. in progress: G. Fournet, Inclusion of blood flow in micro-vessels in a new dMRI signal model, 2013, J.-R. Li and L. Ciobanu
- Ph.D. in progress: S. Schiavi, Homogenized models for Diffusion MRI, 2013, H. Haddar and J.-R. Li
- Ph.D. in progress: K. Van Nguyen, Modeling, simulation and experimental verification of water diffusion in neuronal network of the Aplysia ganglia, 2014, J.-R. Li and L. Ciobanu
- PhD in progress : A. Maury, shape optimization for non-linear structures, 2013, G. Allaire and F. Jouve
- PhD in progress : J.-L. Vié, optimization algorithms for topology design of structures, 2013, G. Allaire and E. Cancès
- PhD in progress : C. Patricot, coupling algorithms in neutronic/thermal-hydraulic/mechanics for numerical simulation of nuclear reactors, 2013, G. Allaire and E. Hourcade
- PhD in progress : A. Talpaert, the direct numerical simulation of vapor bubbles at low Mach number with adaptative mesh refinement, 2013, G. Allaire and S. Dellacherie
- PhD in progress : A. Bissuel, linearized Navier Stokes equations for optimization, floating and aeroaccoustic, 2014, G. Allaire
- PhD in progress : M. Giacomini, Shape optimization and Applications to aeronautics, 2013, O. Pantz and K. Trabelsi
- PhD in progress :P. Geoffroy on topology optimization by the homogenization method in the context of additive manufacturing (Safran Tech, to be defended in 2019), G. Allaire.

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Publications of the year

Doctoral Dissertations and Habilitation Theses

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[2] T. MERCIER. *Data Assimilation and PWR Primary Measurements*, Ecole Doctorale Polytechnique, September 2015, https://pastel.archives-ouvertes.fr/tel-01214018

Articles in International Peer-Reviewed Journals

[3] L. AUDIBERT, G. ALEXANDRE, H. HADDAR. *Identifying defects in an unknown background usingdifferential measurements*, in "Inverse Probl. Imaging", August 2015, vol. 9, n^{o} 3 [*DOI :* 10.3934/IPI.2015.9.625], https://hal.inria.fr/hal-01110270

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