PhD offer: Numerical methods and high performance simulation for 3D imaging in complex media

Context This PhD is part of the OptiGPR3D exploratory action led by IDEFIX and POEMS teams at Inria Saclay, whose objective is to introduce versatile and robust simulation tools that can adapt to complex materials while remaining efficient, in the perspective of making 3D electromagnetic imaging feasible and certifiable through interpretable and optimized inversion methods. With an a priori provided by a classical imaging method, could we design a network of emitters that can provide an optimal illumination of a target structure and a network of receivers that makes it possible to obtain an optimal 3D image? This question is motivated by the need to go beyond the current capabilities of non-destructive testing for buried infrastructures maintained by EDF.

Description In the context of extending the life cycle of EDF facilities, maintenance works rely on *Non-Destructive Testing* (NDT) of infrastructures. In the field of civil engineering, for example, imaging of infrastructures is often needed, both in the preparation of maintenance activities and in hazard studies submitted to safety authorities. The most sought after tools at the moment are those providing the most precise possible image of the core of the structures. As applications, we can mention the 3D localization of reinforcement steels, concrete defects, concrete pathologies, or the search for water pipes. The best techniques currently available, such as GPR (Ground Penetrating Radars), are based on the propagation of electromagnetic waves. The main difficulty comes from the thicknesses to be inspected, the heterogeneities of the materials, and the necessary resolution.

These different aspects make *3D imaging* methods very expensive in terms of time and computational resources. A recent example of 3D imaging for NDT of steam generator tubes [1] required a computation time of 5 hours, with 900 processors, for a single frequency analysis at low resolution. This cost is not acceptable for multi-frequency analyses, as well as for optimizing the acquisition conditions (position, shape and number of sensors), which requires solving several times 3D imaging problems, which themselves rely on *many efficient simulations of the physical model*, called direct problem. Two classes of methods are generally used for the numerical simulation of the physical model: the Finite Element Method (FEM), which is versatile and adapted to heterogeneous materials, and the Boundary Element Method (BEM), which is the most efficient for piecewise homogeneous materials and unbounded domains. In order to optimize the treatment of different types of materials, we propose to systematically couple these two methods. To do so, we wish to explore how to combine FEM and BEM methods in complex multidomain configurations with a domain decomposition approach and the multitrace formalism [2], while allowing both a theoretical analysis and a numerical implementation adapted to parallel computers.

The idea is to isolate homogeneous subdomains (such as homogeneous layers in soil), where BEM method can be applied, and to treat heterogeneous subdomains (such as concrete) by FEM method, with the aim of designing and analyzing strategies for *multidomain FEM-BEM coupling*. The analysis of this multidomain coupling becomes problematic in the case where the interfaces between the subdomains intersect and form *junction points* (see the yellow circles in Figure 1). It is therefore necessary to deal with this case in order to develop a sufficiently versatile tool that can adapt to different physical configurations, and that is efficient for 3D problems.

The objective of the PhD will be to explore new approaches of *multitrace FEM-BEM coupling*, using the different variants of the multitrace formalism, which can address the junction points problem, but to which the FEM-BEM coupling aspect has to be added. Moreover, many choices on the type of *information communicated between subdomains* can be made, and these have a

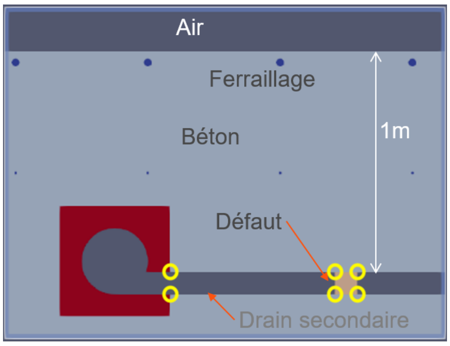

Figure 1: Hydroelectric dam drains, example of a configuration with junction points (in yellow).

direct impact on the local FEM and BEM formulations in the subdomains. In addition to the theoretical implications of the different formulation choices, it is also essential to design parallel methods for efficient resolution in the context of *high performance computing*. It will then be necessary to investigate the construction of robust preconditioners, as well as recycling techniques and block methods, adapted to the solution and optimization of imaging problems, which involve linear systems with several right-hand sides.

Requirements 2nd year Master student or 3rd year Engineering School student, with skills in numerical analysis (PDE, finite element method, linear algebra . . .) and programming (e.g. C/C++, Python, . . .).

Location Unité de Mathématiques Appliquées (UMA), ENSTA Paris, 828, Boulevard des Maréchaux, 91762 Palaiseau, France.

Duration 3 years, starting after September 2023.

Salary Paid according to Inria scale for PhD students.

Supervisors

- Marcella Bonazzoli (IDEFIX Inria team, UMA, ENSTA Paris, marcella.bonazzoli@inria.fr)
- Xavier Claeys (LJLL, Sorbonne Université, xavier.claeys@sorbonne-universite.fr)
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Collaborators Lorenzo Audibert (EDF R&D, IDEFIX team), Houssem Haddar (Inria, IDEFIX team) and Frédéric Taillade (EDF R&D, IDEFIX team).

To apply Email the three supervisors with a curriculum vitae, transcripts of Bachelor and Master (or equivalent) grades, recommendation letters (optional), and reports on any projects or internships carried out during Bachelor or Master. *A Master internship subject preceding this PhD offer is available.*

References

[1] Lorenzo Audibert, Hugo Girardon, Houssem Haddar, and Pierre Jolivet. Inversion of Eddy-Current Signals Using a Level-Set Method and Block Krylov Solvers. Preprint, 2021. URL: https://hal.archives-ouvertes.fr/hal-03043491.

[2] Xavier Claeys and Emile Parolin. Robust treatment of cross-points in optimized Schwarz methods. *Numerische Mathematik*, 2022. URL: https://arxiv.org/pdf/2003.06657.pdf, doi:10.1007/s00211-022-01288-x.