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Project-Team COMMEDIA

Computational mathematics for bio-medical applications

IN COLLABORATION WITH: Laboratoire Jacques-Louis Lions (LJLL)

DOMAIN

Digital Health, Biology and Earth

THEME

Modeling and Control for Life Sciences

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Project-Team COMMEDIA

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Computer sciences and digital sciences

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2 Overall objectives

COMMEDIA is a joint project-team of the Inria Research Center of Paris and the Jacques-Louis Lions Laboratory (LJLL) of Sorbonne Université and CNRS (UMR7598). The research activity of COMMEDIA focuses on the numerical simulation of bio-fluid flows in the human body, more specifically, blood flows in the cardiovascular system and air flows in the respiratory system. These simulations are intended to complement available clinical data with the following purpose: help clinicians or bio-engineers to enhance the understanding of physiological phenomena, to improve diagnosis and therapy planning or to optimize medical devices. The main main objectives of COMMEDIA are:

- the development of appropriate mathematical models and efficient numerical methods for the simulations and for the interaction of simulations with measured data;
- the mathematical analysis of these models and numerical techniques;
- the development and validation of scientific computing software which implements these numerical techniques.

A distinctive feature of the mathematical models considered in COMMEDIA is that they often couple different types of partial differential equations (PDEs). This heterogeneous character in the models is a mathematical manifestation of the multi-physics nature of the considered problems.

3 Research program

3.1 Multi-physics modeling and simulation

The research activity in terms of modeling and simulation (i.e., the so-called forward problem) is driven by two application domains related to the cardiovascular and the respiratory systems.

3.1.1 Cardiovascular hemodynamics

We distinguish between *cardiac hemodynamics* (blood flow inside the four chambers of the heart) and *vascular hemodynamics* (blood flow in the vessels of the body).

Cardiac hemodynamics. The numerical simulation of cardiac hemodynamics presents many difficulties. We can mention, for instance, the large deformation of the cardiac chambers and the complex fluid-structure interaction (FSI) phenomena between blood, the valves and the myocardium. Blood flow can be described by the incompressible Navier-Stokes equations which have to be coupled with a bio-physical model of the myocardium electro-mechanics and a mechanical model of the valves. The coupling between the fluid and the solid media is enforced by kinematic and dynamic coupling conditions, which guarantee the continuity of velocity and stresses across the interface. In spite of the significant advances achieved since the beginning of this century (see, e.g., [61, 62, 59, 64, 52]), the simulation of all the fluid-structure interaction phenomena involved in the heart hemodynamics remains a complex and challenging problem.

Heart valves are definitely a bottleneck of the problem, particularly due to their fast dynamics and the contact phenomena at high pressure-drops. Computational cost is recognized as one of the key difficulties, related to the efficiency of the FSI coupling method and the robustness of the contact algorithm. Furthermore, the numerical discretization of these coupled systems requires to deal with unfitted fluid and solid meshes, which are known to complicate the accuracy and/or the robustness of the numerical approximations (see Section 3.3.2 below).

The ultimate goal of the proposed research activity is the simulation of the complete fluid-structure-contact interaction phenomena involved within the heart. Most of this work will be carried out in close collaboration with the M3DISIM project-team, which has a wide expertise on the modeling, simulation

and estimation of myocardium electro-mechanics. We will also consider simplified approaches for cardiac hemodynamics (see, e.g., [33, 47, 50]). The objective is to develop mathematically sound models of reduced valve dynamics with the purpose of enhancing the description of the pressure dynamics right after the opening/closing of the valve (traditional models yield spurious pressure oscillations).

Vascular hemodynamics. The modeling and simulation of vascular hemodynamics in large vessels has been one of the core research topics of some members of COMMEDIA, notably as regards the fluid-structure interaction phenomena. Here we propose to investigate the modeling of pathological scenarios, such as the hemorrhage phenomena in smaller vessels. Modeling of hemorrhage is motivated by the medical constatation that, after a primary vessel wall rupture, secondary vessel wall ruptures are observed. Biologists postulate that the mechanical explanation of this phenomena might be in the change of applied stress due to blood bleeding. We propose to model and simulate the underlying coupled system, blood vessel flow through the external tissue, to estimate the effect of the subsequent stress variation.

3.1.2 Respiratory flows

The motivation of the proposed research activities is to develop a hierarchy of easily parametrizable models allowing to describe and efficiently simulate the physical, mechanical and biological phenomena related to human respiration, namely,

ventilation, particle deposition, gas diffusion and coupling with the circulatory system.

Ventilation. The current modeling approaches (either 3D–0D coupled models where the 3D Navier-Stokes equations are solved in truncated geometries of the bronchial tree with appropriate lumped boundary conditions, or 0D–3D coupled models where the lung parenchyma is described by a 3D elastic media irrigated by a simplified bronchial tree) provide satisfactory results in the case of mechanical ventilation or normal breathing. Realistic volume-flow phase portraits can also be simulated in the case of forced expiration (see [35, 44, 67]), but the magnitude of the corresponding pressure is not physiological. The current models must be enriched since they do not yet correctly describe all the physiological phenomena at play. We hence propose to extend the 0D–3D (bronchial tree–parenchyma) model developed in the team, by considering a non-linear, viscoelastic and possibly poro-elastic description of the parenchyma with appropriate boundary conditions that describe ribs and adjacent organs and taking into account an appropriate resistive model.

So far, the motion of the trachea and proximal bronchi has been neglected in the ventilation models (see, e.g., [69]). These features can be critical for the modeling of pathologic phenomena such as sleep apnea and occlusion of the airways. This would be a long-term goal where fluid-structure interaction and the possible contact phenomena will be taken into account, as in the simulation of cardiac hemodynamics (see Section 3.1.1).

Aerosol and gas diffusion. The dynamics of aerosols in the lung have been widely studied from the mathematical modeling standpoint. They can be described by models at different scales: the microscopic one for which each particle is described individually, the mesoscopic (or kinetic) one for which a density of probability is considered, or the macroscopic one where reaction-diffusion equations describing the behavior of the constituant concentration are considered. The objective of COMMEDIA will mainly be to develop the kinetic approach that allows a precise description of the deposition area at controlled computational costs. Part of this study could be done in collaboration with colleagues from the Research Center for Respiratory Diseases at Inserm Tours (UMR1100).

The macroscopic description is also appropriate for the diffusion of gases (oxygen and carbon dioxide) in the bronchial tree (see [63]). Regarding the influence of the carrier gas, if the patient inhales a different mixture of air such as a Helium-Oxygen mixture, the diffusion mechanisms could be modified. In this context, the goal is to evaluate if the cross-diffusion (and thus the carrier gas) modifies the quantities of oxygen diffused. Part of this work will be carried out in collaboration with members of the LJLL and of the MAP5.

As a long term goal, we propose to investigate the coupling of these models to models of diffusion in the blood or to perfusion models of the parenchyma, and thus, have access thanks to numerical simulations to new indices of ventilation efficiency (such as dissolved oxygen levels), depending on the pathology considered or the resting or exercise condition of the patient.

3.2 Simulation with data interaction

The second research axis of COMMEDIA is devoted to the interaction of numerical simulations with measured data. Several research directions related to two specific applications are described below: blood flows and cardiac electrophysiology, for which the mathematical models have been validated against experimental data. This list is not exhaustive and additional problems (related to cardiac and respiratory flows) shall be considered depending on the degree of maturity of the developed models.

3.2.1 Fluid flow reconstruction from medical imaging

A first problem which is currently under study at COMMEDIA is the reconstruction of the flow state from Doppler ultrasound measurements. This is a cheap and largely available imaging modality where the measure can be interpreted as the average on a voxel of the velocity along the direction of the ultrasound beam. The goal is to perform a full-state estimation in a time compatible with a realistic application.

A second problem which is relevant is the flow and wall dynamics reconstruction using 4D-flow MRI. This imaging modality is richer than Doppler ultrasound and provides directly a measure of the 3D velocity field in the voxels. This enables the use of direct estimation methods at a reduced computational cost with respect to the traditional variational data assimilation approaches. Yet, the sensitivity of the results to subsampling and noise is still not well understood.

We also propose to address the issues related to uncertainty quantification. Indeed, measurements are corrupted by noise and the parameters as well as the available data of the system are either hidden or not known exactly (see [58]). This uncertainty makes the estimation difficult and has a large impact on the precision of the reconstruction, to be quantified in order to provide a reliable tool.

3.2.2 Inverse problem in electro-cardiography

The objective of the inverse problem in electro-cardiography is to recover information about the cardiac electrical activity from electrical measurements on the body surface (for instance from electrocardiograms). We propose to investigate approaches based on recent methods for the Cauchy problem reported in [41]. Basically, the idea consists in regularizing the discrete inverse problem using stabilized finite element methods, without the need of integrating a priori knowledge of the solution, only regularity on the exact solution is required.

3.2.3 Safety pharmacology

One of the the most important problems in pharmacology is cardio-toxicity (see [57]). The objective is to predict whether or not a molecule alters in a significant way the normal functioning of the cardiac cells. This problem can be formulated as inferring the impact of a drug on the ionic currents of each cell based on the measured electrical signal (e.g., electrograms from Micro-Electrodes Arrays). The proposed approach in collaboration with two industrial partners (NOTOCORD and Ncardia) consists in combining available realistic data with virtual ones obtained by numerical simulations. These two datasets can be used to construct efficient classifiers and regressors using machine learning tools (see [40]) and hence providing a rapid way to estimate the impact of a molecule on the electrical activity. The methodological aspects of this work are addressed in Section 3.3.3.

3.3 Methodological core

The work described in this section is aimed at investigating fundamental mathematical and numerical problems which arise in the first two research axes.

3.3.1 Mathematical analysis of PDEs

The mathematical analysis of the multi-scale and multi-physics models are a fundamental tool of the simulation chain. Indeed, well-posedness results provide precious insights on the properties of solutions of the systems which can, for instance, guide the design of the numerical methods or help to discriminate between different modeling options.

Fluid-structure interaction. Most of the existing results concern the existence of solutions locally in time or away from contacts. One fundamental problem, related to the modeling and simulation of valve dynamics (see Sections 3.1.1 and 3.3.2), is the question of whether or not the model allows for contact (see [56, 54]). The proposed research activity is aimed at investigating the case of both immersed rigid or elastic structures and explore if the considered model allows for contact and if existence can be proved beyond contact. The question of the choice of the model is crucial and considering different types of fluid (newtonian or non newtonian), structure (smooth or rough, elastic, viscoelastic, poro-elastic), or various interface conditions has an influence on whether the model allows contact or not.

Fluid–structure mixture. The main motivation to study fluid-solid mixtures (i.e., porous media consisting of a skeleton and connecting pores filled with fluid) comes from the modeling of the lung parenchyma and cerebral hemorrhages (see Sections 3.1.1–3.1.2). The Biot model is the most widely used in the literature for the modeling of poro-elastic effects in the arterial wall. Here, we propose to investigate the recent model proposed by the M3DISIM project-team in [46], which allows for nonlinear constitutive behaviors and viscous effects, both in the fluid and the solid. Among the questions which will be addressed, some of them in collaboration with M3DISIM, we mention the justification of the model (or its linearized version) by means of homogenization techniques and its well-posedness.

Fluid–particle interaction. Mathematical analysis studies on the Navier-Stokes-Vlasov system for fluid-particle interaction in aerosols can be found in [37, 39]. We propose to extend these studies to more realistic models which take into account, for instance, changes in the volume of the particles due to humidity.

3.3.2 Numerical methods for multi-physics problems

In this section we describe the main research directions that we propose to explore as regards the numerical approximation of multi-physics problems.

Fluid-structure interaction. The spatial discretization of fluid-structure interaction (FSI) problems generally depends on the amount of solid displacement within the fluid. Problems featuring moderate interface displacements can be successfully simulated using (moving) fitted meshes with an arbitrary Lagrangian-Eulerian (ALE) description of the fluid. This facilitates, in particular, the accurate discretization of the interface conditions. Nevertheless, for problems involving large structural deflections, with solids that might come into contact or that might break up, the ALE formalism becomes cumbersome. A preferred approach in this case is to combine an Eulerian formalism in the fluid with an unfitted mesh discretization, in which the fluid-structure interface deforms independently of a background fluid mesh. In general, traditional unfitted mesh approaches (such as the immersed boundary and the fictitious domain methods [66, 36, 53, 34]) are known to be inaccurate in space. These difficulties have been recently circumvented by a Nitsche-based cut-FEM methodolgy (see [31, 42]). The superior accuracy properties of cut-FEM approaches comes at a price: these methods demand a much more involved computer implementation and require a specific evaluation of the interface intersections.

As regards the time discretization, significant advances have been achieved over the last decade in the development and the analysis of time-splitting schemes that avoid strong coupling (fully implicit treatment of the interface coupling), without compromising stability and accuracy. In the vast majority these studies, the spatial discretization is based on body fitted fluid meshes and the problem of accuracy remains practically open for the coupling with thick-walled structures (see, e.g., [51]). Within the unfitted mesh framework, splitting schemes which avoid strong coupling are much more rare in the literature.

Computational efficiency is a major bottleneck in the numerical simulation of fluid-structure interaction problems with unfitted meshes. The proposed research activity is aimed at addressing these issues. Another fundamental problem that we propose to face is the case of topology changes in the fluid, due to contact or fracture of immersed solids. This challenging problem (fluid-structure-contact-fracture interaction) has major role in many applications (e.g., heart valves repair or replacement, break-up of drug-loaded micro-capsules) but most of the available studies are still merely illustrative. Indeed, besides the numerical issues discussed above, the stability and the accuracy properties of the numerical approximations in such a singular setting are not known.

Fluid–particle interaction and gas diffusion.

Aerosols can be described through mesoscopic equations of kinetic type, which provide a trade-off between model complexity and accuracy. The strongly coupled fluid-particle system involves the

incompressible Navier-Stokes equations and the Vlasov equation. The proposed research activity is aimed at investigating the theoretical stability of time-splitting schemes for this system. We also propose to extend these studies to more complex models that take into account the radius growth of the particles due to humidity, and for which stable, accurate and mass conservative schemes have to be developed.

As regards gas diffusion, the mathematical models are generally highly non-linear (see, e.g., [63, 65, 38]). Numerical difficulties arise from these strong non linearities and we propose to develop numerical schemes able to deal with the stiff geometrical terms and that guarantee mass conservation. Moreover, numerical diffusion must be limited in order to correctly capture the time scales and the cross-diffusion effects.

3.3.3 Statistical learning and mathematical modeling interactions

Machine learning and in general statistical learning methods (currently intensively developed and used, see [32]) build a relationship between the system observations and the predictions of the QoI based on the *a posteriori* knowledge of a large amount of data. When dealing with biomedical applications, the available observations are signals (think for instance to images or electro-cardiograms, pressure and Doppler measurements). These data are high dimensional and the number of available individuals to set up precise classification/regression tools could be prohibitively large. To overcome this major problem and still try to exploit the advantages of statistical learning approaches, we try to add, to the a posteriori knowledge of the available data an *a priori* knowledge, based on the mathematical modeling of the system. A large number of numerical simulations is performed in order to explore a set of meaningful scenarios, potentially missing in the dataset. This *in silico* database of virtual experiments is added to the real dataset: the number of individuals is increased and, moreover, this larger dataset can be used to compute semi-empirical functions to reduce the dimension of the observed signals.

Several investigations have to be carried out to systematically set up this framework. First, often there is not a single mathematical model describing a physiological phenomenon, but hierarchies of model of different complexity. Every model is characterized by a model error. How can this be accounted for? Moreover, several statistical estimators can be set up and eventually combined together in order to improve the estimations (see [60]). Other issues have an actual impact and has to be investigated: what is the optimal number of *in silico* experiments to be added? What are the most relevant scenarios to be simulated in relation to the statistical learning approach considered in order to obtain reliable results? In order to answer to these questions, discussions and collaborations with statistics and machine learning groups have to be developed.

3.3.4 Tensor approximation and HPC

Tensor methods have a recent significant development because of their pertinence in providing a compact representation of large, high-dimensional data. Their applications range from applied mathematics and numerical analysis to machine learning and computational physics. Several tensor decompositions and methods are currently available (see [55]). Contrary to matrices, for tensors of order higher or equal to three, there does not exist, in general, a best low rank approximation, the problem being ill posed (see [68]). Two main points will be addressed: (i) The tensor construction and the multi-linear algebra operations involved when solving high-dimensional problems are still sequential in most of the cases. The objective is to design efficient parallel methods for tensor construction and computations; (ii) When solving high-dimensional problems, the tensor is not assigned; instead, it is specified through a set of equations and tensor data. Our goal is to devise numerical methods able to (dynamically) adapt the rank and the discretization (possibly even the tensor format) to respect the chosen error criterion. This could, in turn, improve the efficiency and reduce the computational burden.

These sought improvements could make the definition of parsimonious discretizations for kinetic theory and uncertainty quantification problems (see Section 3.2.1) more efficient and suitable for a HPC paradigm. This work will be carried out in collaboration with Olga Mula (Université Paris-Dauphine) and the ALPINES and MATHERIALS project-teams.

4 Application domains

4.1 Cardiovascular hemodynamics

The heart is a double pump whose purpose is to deliver blood to the tissue and organs of the body. This function is made possible through the opening and closing of the heart valves. Cardiac diseases generally manifest by affecting the pumping function of the heart. Numerical simulations of cardiac hemodynamics, in normal and pathological conditions, are recognized as a tool of paramount importance for improving the understanding, diagnosis and treatment of cardiac pathologies, and also for the development of implantable devices (see, e.g., [64, 45]). As an example, we can mention the case of cardiac mitral valve regurgitation, one of the most common heart valve diseases. For this pathology, clinical data are known to be insufficient for determining the optimal timing for surgery, the best surgical strategy and the long-term outcome of a surgical repair. Contrary to imaging techniques, numerical simulations provide local information, such as pressure and stresses, which are of fundamental importance for the prediction of the mechanical behavior of native valves and of implantable devices.

4.2 Respiratory flows

Respiration involves the transport of air through the airways from the mouth to the alveoli of the lungs. These units where diffusion of oxygen and carbon dioxide take place, are surrounded by a viscoelastic medium (the parenchyma) consisting of blood vessels and collagen fibers. Air flows due to the displacement of the diaphragm, which drives the pulmonary parenchyma. Accidental inhalations of foreign bodies or pathologies such as asthma, emphysema and fibrosis might prevent the lung of fulfilling its function. Therapies mostly use aerosols (set of small particles, solid or liquid), which must reach the specific areas of the lung targeted for treatment. Understanding the airflow mechanisms within the respiratory network is a fundamental ingredient for predicting the particles motion and their deposition (see, e.g., [43]). Moreover, understanding of the gas diffusion in the lung is also of major importance since the main fonction of this organ is to deliver oxygen to the blood.

4.3 Safety pharmacology

The problem of safety pharmacology can be summarized as follows: given a molecule which is a candidate to become a drug, is its use dangerous due to side effects? Among all the different problems to be addressed, one of the most relevant questions in pharmacology is cardio-toxicity (see [57]). More precisely, the objective is to determine whether or not a molecule alters in a significant way the normal functioning of the cardiac cells. To answer these questions, the CiPA initiative promotes the introduction of novel techniques and their standardisation (see [49]). One of the proposed tests of the CiPA panel is to measure the the electrical activity using Micro-Electrodes Array: these are microchips that record the electrical activity of an ensemble of cells. The task is to infer the impact of a drug on the ionic currents of each cell based on the electrical signal measured (electrograms) and, in perspective, to be able to assess whether a molecule can induce arrhythmia (see [48]).

5 New software and platforms

5.1 New software

5.1.1 FELiScE

Name: Finite Elements for Life SCiences and Engineering problems

Keywords: Finite element modelling, Cardiac Electrophysiology, Cardiovascular and respiratory systems

Functional Description: FELiScE is a finite element code which the M3DISIM and REO project-teams initially jointly develop in order to build up on their respective experiences concerning finite element simulations. One specific objective of this code is to provide in a unified software environment all the state-of-the-art tools needed to perform simulations of the complex respiratory and cardiovascular models considered in the two teams – namely involving fluid and solid

mechanics, electrophysiology, and the various associated coupling phenomena. FELISCE is written in C++, and may be later released as an opensource library. FELiScE was registered in July 2014 at the Agence pour la Protection des Programmes under the Inter Deposit Digital Number IDDN.FR.001.350015.000.S.P.2014.000.10000.

URL: https://team.inria.fr/commedia/software/felisce/

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5.1.2 FELiScE-NS

Keywords: Incompressible flows, Thin-walled solids

Functional Description: FELiScE-NS is a set finite elements solvers for incompressible fluids (fractional-step schemes) and non-linear thin-walled structures (3D shells, and 2D curved beams) developed in the framework of the FELiScE library. FELiSCe-NS was registered in 2018 at the Agence pour la Protection des Programmes Inter Deposit Digital Number IDDN.FR.001.270015.000.S.A.2018.000.31200.

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5.1.3 DCIMaL

Keyword: Cardiac Electrophysiology

Functional Description: DCIMaL is a Python and C++ software for safety pharmacology studies and particularly field potentials signals measured with micro-electrode array (MEA). The software includes a solver for field potential simulations and a dictionary of entries corresponding to features which can be extracted from real or simulated potential signals. It also includes an algorithm for drug classification (channel blockade or torsadogenic risk) and a tool for estimating ion channel activity (based on the CMAES library). DCIMaL was registered in 2018 at the Agence pour la Protection des Programmes Inter Deposit Digital Number IDDN.FR.001.270003.000.S.P.2018.000.31230

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Participants: Fabien Raphel, Jean-Frederic Gerbeau, Damiano Lombardi

5.1.4 ADAPT

Name: Adaptive Dynamical Approximation via Parallel Tensor methods

Keywords: Scientific computing, Tensor decomposition, Partial differential equation

Functional Description: ADAPT is a library containing methods for scientific computing based on tensors. In many fields of science and engineering we need to approximate the solution of high-dimensional problems. In this library we propose a collection of methods to parsimoniously discretise high-dimensional problems. These methods are mainly based on tensors.

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6 New results

6.1 Fluid flow reconstruction from medical imaging

Participants: Mocia Agbalessi, Miguel Ángel Fernández Varela, Felipe Galarce Marin, Damiano Lombardi, Olga Mula
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In [21] we propose a numerical method to perform the dynamical tracking of the blood vessel walls when 4d-flow MRI data are available. The proposed method is based on a Kalman filter. The Eulerian information provided by the 4d-flow measurements are converted into a Lagrangian information about position and velocity of the structure by means of a minimising movement scheme. Several numerical test cases are proposed to assess the method performances and a realistic case on a 3d aorta is shown.

In [29] we study how to deal with geometric variability when performing state estimation by using projection-based Reduced Order Models (ROM). When the domain geometry varies, if we wnated to use projection-based ROMs we should compute a database for every new geometry. In this contribution we propose and analyse a method to: define a physics-geometry based distance between sets of solutions in different domains; a method to transport subspaces basis functions between different geometries; a ROM strategy to solve direct and inverse problems. Several synthetic test cases are proposed.

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6.2 Numerical methods for multi-physics problems

Participants: Muriel Boulakia, Céline Grandmont, Miguel Ángel Fernández Varela, Marina Vidrascu, Fannie Gerosa.

In [26] we present a loosely coupled, non-iterative time-splitting scheme based on Robin-Robin coupling conditions. We apply a novel unified analysis for this scheme applied to both a Parabolic/Parabolic coupled system and a Parabolic/Hyperbolic coupled system. We show for both systems that the scheme is stable, and the error converges quasi-optimally.

In [14] we present a new approach for the mechanically consistent modelling and simulation of fluid-structure interactions with contact. The fundamental idea consists of combining a relaxed contact formulation with the modelling of seepage through a porous layer of co-dimension 1 during contact. For the latter, a Darcy model is considered in a thin porous layer attached to a solid boundary in the limit of infinitesimal thickness. In combination with a relaxation of the contact conditions the computational model is both mechanically consistent and simple to implement. We analyse the approach in detailed numerical studies with both thick-and thin-walled solids, within a fully Eulerian and an immersed approach for the fluid-structure interaction and using fitted and unfitted finite element discretisations.

In [25] we develop a fictitious domain method to approximate a Dirichlet problem on a domain with small circular holes. To address the case of many small inclusions or exclusions, we propose a reduced model based on the projection of the homogeneous Dirichlet boundary constraint on a finite dimensional approximation space. We analyze the existence of the solution of this reduced problem and prove its convergence towards the limit problem without holes. We next obtain an estimate of the gap between the solution of the reduced model and the solution of the full initial model with small holes, the convergence rate depending on the size of the inclusion and on the number of modes of the finite dimensional space. The numerical discretization of the reduced problem is addressed by the finite element method, using a computational mesh that does not fit to the holes. The approximation properties of the finite element

method are analyzed by a-priori estimates and confirmed by numerical experiments. elliptic differential equations, small inclusions, asymptotic analysis, approximated numerical method.

In [11] We address the question of the modelling of the fluid-structure interactions for a microcapsule enclosed by a finite-thickness wall, and of the prediction of the buckling behaviour when it is subjected to large displacements and deformations. Specifically, we model the strong coupling between the solid (the wall dynamics) and fluid (the flow inside and outside the capsule) mechanics, for a wall material that can be strain-hardening or softening, while accounting for the bending resistance due to thickness. The fluid flow is assumed to be inertialess on the capsule scale, which allows the use of the boundary integral formulation for the fluid velocity. We discuss the different simplifications that are made when designing a fluid-shell interaction model for large deformations, and present a shear-membrane-bending (SMB) shell model that allows for a nonlinear wall stretching law. The performance of the model, as compared to a simple membrane model where bending resistance is neglected, is illustrated on a generic example: we consider an initially ellipsoidal capsule, freely suspended in a plane hyperbolic flow, that is subjected to such stringent deformation, that its short axis becomes the long one. We show that the simple membrane model predicts reasonably well the overall shape of the capsule, but cannot capture the detailed post buckling behaviour, for which a robust shell model is necessary. The SMB shell model complies with dominant membrane effects, remains stable even under large deformation and avoids numerical locking. It allows predicting post-buckling behaviour, which depends on the material constitutive law.

6.3 Statistical learning and mathematical modeling interactions

Participants: Damiano Lombardi, Fabien Raphel.

In [18] we investigate a method to enrich experimental datasets by means of sets of numerical simulations for classification problems. In several realistic applications, the available training set could be scarce (in terms of number of available samples). A mathematical model is an a priori source of information about how the system under scrutiny works. We therefore would like to incorporate this information in the training set. In this contribution we propose a systematic way to integrate a set of numerical simulations to an available experimental dataset in such a way that the classification performances (determined by a suitably defined objective function) are maximised.

6.4 Tensor approximation and HPC

Participants: Damiano Lombardi, Maria Fuente Ruiz.

In [12] we propose a certified method to approximate a given multivariate function (defined on a domain which is a cartesian product of domains) as a sum of Tensor Trains. Contrary to what is usually done, neither the ranks (number of terms in the tensor approximation) nor the order of the variables are fixed a priori. Instead, they are computed based on a parsimony criterion. We proved the convergence of the method (in a discrete setting) and tested it on several bechmarks.

In [23] we propose a numerical method, based on Alternating Direction, to solve a multi-linear system. The method is defined in such a way that sequences of linear system solving can be performed by using classical methods (with known, efficient preconditionners). Under mild assumptions, we proved that the method converges monotonically to the solution. Several test cases on parametric partial differential equations are provided.

In [30] we investigate how a Tensor Train representation of a system state can be exploited in view of performing fast state estimation. When we cast state estimation as an optimal recovery problem, the advantage is that we can perform state estimation without performing parameter estimation. In this contribution, the system state, as a function of space-time-parameters, is approximated as a Tensor Train. A variational and a sequential approaches are proposed to solve state estimation when the observations

are sets of linear forms applied to the state. Some proofs concerning the errors are proposed as well as three different numerical experiments.

6.5 Miscellaneous

Participants: Damiano Lombardi, Olga Mula.

In [22] we investigated the possibility of using information based quantities to analysing experimental protocols for estimating soft tissue properties. In particular, we can devise how to proceed in biaxial experiments in order to maximise the amount of information the measurements convey about the soft tissue parameters to be estimated.

7 Bilateral contracts and grants with industry

7.1 Bilateral contracts with industry

Notocord Systems

Participants: Damiano Lombardi *(coordinator)*, Fabien Raphel.

This work is devoted to the investigation on new approaches and efficient algorithms in the context of safety pharmacology and the analysis of biological signals.

Casis

Participants: Mocia Agbalessi, Miguel Ángel Fernández Varela *(coordinator)*, Damiano Lombardi.

This work is devoted to the combination of 4D-MRI data and fluid-structure interaction models of blood flow to asses indicators of aneurysm rupture.

Systol Dynamics

Participants: Marguerite Champion, Miguel Ángel Fernández Varela *(coordinator)*, Céline Grandmont, Marina Vidrascu, Fabien Vergent.

This work is devoted to the modeling and numerical simulation of implantable aortic blood pumps.

8 Partnerships and cooperations

8.1 International initiatives

8.1.1 Inria associate team not involved in an IIL or an international program

IMFIBIO: Innovative Methods for Forward and Inverse problems in BIO-medical applications

Participants: Muriel Boulakia *(coordinator)*, Marguerite Champion, Daniele Carlo Corti, Miguel Angel Fernandez Varela, Céline Grandmont.

Duration: 2020-2022

Coordinator: Muriel Boulakia

Partners: Department of Mathematics, University College London (UK)

Summary: The purpose of the IMFIBIO Associate Team is to exploit the complementary expertise of both partners in mathematical analysis, numerical analysis, scientific computing and data assimilation in order to develop innovative methods for the study of forward and inverse problems in the context of bio-medical applications.

Web site: team.inria.fr/imfibio

8.1.2 Visits to international teams

Research stays abroad

- Céline Grandmont : Member of the research group "Analyse et équations aux dérivées partielles" at ULB Belgium

8.2 European initiatives

8.2.1 FP7 & H2020 projects

INSPIRE: INnovation in Safety Pharmacology for Integrated cardiovascular safety assessment to REduce adverse events and late stage drug attrition

Participants: Muriel Boulakia, Sara Costa Faya, Miguel Angel Fernandez Varela, Céline Grandmont, Haibo liu, Damiano Lombardi *(coordinator)*
.

Funding: Horizon 2020 - MSCA-ITN

Duration: 2020-2023

Coordinator: University of Antwerp

Local coordinator: Damiano Lombardi

Partners: see the link

Summary: INSPIRE is an European Training Network (ETN) projet funding 15 Early Stage Researchers (ESRs) aimed to exploit innovative techniques for better assessment and prediction of cardiovascular safety liabilities.

Web site: www.uantwerpen.be/en/projects/inspire-safety-pharmacology

8.3 National initiatives

8.3.1 ANR

ADAPT: Adaptive Dynamical Approximations by Parallel Tensor methods

Participants: Maria Fuente-Ruiz, Damiano Lombardi *(coordinator)*, Olga Mula
.

Funding: ANR JCJC

Duration: 2018-2022

Coordinator: Damiano Lombardi

Summary: The main goal of the ANR is to investigate the numerical approximation of the solution of high-dimensional problems. In particular, the applications that motivate this study are the Uncertainty Quantification and the Kinetic theory. The main objective is to construct in an adaptive way parsimonious discretisations starting from arbitrarily chosen separated discretisations.

Web site: project.inria.fr/adapt

SIMR: Simulation and Imaging for Mitral Regurgitation

Participants: Daniele Carlo Corti, Miguel Ángel Fernández Varela *(coordinator)*, Fannie Gerosa, Céline Grandmont, Marina Vidrascu.

Funding: ANR PRC

Duration: 2020-2023

Coordinator: Miguel Ángel Fernández Varela

Partners: CREATIS, HCL, LGEF, M3DISIM, TIMC

Summary: The SIMR project aims at evaluating the physical consequences of mitral repair using efficient numerical simulations, advanced imaging techniques and an innovative measurement tools in a clinical study.

Web site: project.inria.fr/simr

9 Dissemination

9.1 Promoting scientific activities

9.1.1 Scientific events: organisation

- Damiano Lombardi
  - Co-organizer of the CEMRACS 2021 summer school, 6 weeks, about 100 participants.
  - Co-organizer of Inria-LJLL meeting in scientific computing
- Olga Mula
  - Co-organizer of the CEMRACS 2021 summer school.
  - Annual Workshop of GdR MaNu. Oct. 25-27

9.1.2 Journal

Member of the editorial boards

- Céline Grandmont
  - Member of the editorial board of Mathematical Modelling of Natural Phenomena
  - Member of the editorial board of Journal of Mathematical Fluid Mechanics
  - Member of the editorial board of M2AN
- Olga Mula
  - Member of the editorial board of Calcolo
  - Associate Editor for Advances in Computational Mathematics
  - Vice-President of the GdR MaNu.

9.1.3 Research administration

- Miguel Ángel Fernández Varela
  - Head of Science, Inria Paris
  - Member of the Inria Evaluation Committee
- Céline Grandmont
  - Member of the Inria Parity Committee
  - Member of the Inria Evaluation Committee
  - Co-coordination of the Inria Evaluation Committee working group on Inria scientific Strategy

9.1.4 Conferences

- Daniele Corti
  - Contributed talk in minisymposium, iHEART Modelling the Cardiac Function (Online Conference), July 2021, Milano, Italy
- Céline Grandmont
  - Invited Conference, Lake Como School "Partial Differential Equations on Mathematical Physics and Applications", sept. 2021
  - Online Seminar, Konstanz Univ., juillet 2021
- Damiano Lombardi
  - Laboratoire Jacques Louis Lions, Sorbonne Université, 03/2021, *Adaptive tensor methods for scientific computing.*
  - Glasgow Computational Engineering Centre, University of Glasgow, 04/2021, *Adaptive tensor methods for scientific computing.*
  - Journée SIGMA, Sorbonne Université, 10/2021, *Adaptive tensor methods for scientific computing*
  - Laboratoire des Mathématiques d'Orsay, Université Paris Sud, 10/2021 *Adaptive tensor methods for scientific computing.*
  - Scientific Computing group, Konstanz University, 11/2021, *Adaptive tensor methods for scientific computing.*
  - Invited keynote in mini-symposium, SIMAI 2020-2021, Parma, *Data Assimilation in haemodynamics.*
  - Invited talk, IFPEN, workshop on model reduction, *Tensor methods and model reduction.*
- Mihai Nechita
  - Contributed talk, Romanian Academy Conference of Scientific Research, November 2021
  - Contributed talk, Cluj Academic Days, October 2021
  - Contributed talk, IFIP TC7 Conference on System Modeling and Optimization, September 2021
  - Seminar, Control in Times of Crisis, January 2021
- Fabien Raphel
  - Contributed talk at SIAM Annual Meeting UQ minisymposium, July 2021, Online.
  - Invited talk at INRAE MaIAGE team, April 2021, Online.
- Fabien Vergnet

  - Seminar, Modeling and scientific computation, September 2021, LAGA, Univ. Sorbonne Paris Nord.
  - Seminar, Analysis, scientific computation and optimization, June 2021, IMAG, Univ. Montpellier.

9.2 Teaching - Supervision - Juries

9.2.1 Teaching

- Licence:
  - Olga Mula
    * Pre-course on calculus for first year students. 2 groups. 28 hours per group.
    * TD for Probability course for second year students. 1 group. 43 hours.
  - Fabien Vergnet
    * Numerical analysis and ODE, 58h, L3, Polytech Sorbonne, Sorbonne Université.
    * Nonlinear systems and optimization, 30h, L3, Polytech Sorbonne, Sorbonne Université.
    * Dynamical systems, 12h, L3, Polytech Sorbonne, Sorbonne Université.
    * Differential equations, 18h, L2, Polytech Sorbonne, Sorbonne Université.
- Master:
  - Muriel Boulakia
    * Fluid dynamics in life sciences, mathematical and computational viewpoints, 12h, M2, Sorbonne Université
    * TD Optimization, 18h, M1, Sorbonne Université
    * Preparatory course for teaching admission examination “Agrégation”, 40h, M2, Sorbonne Univ
  - Miguel Ángel Fernández Varela
    * TD Scientific computing for large linear systems, 18h, M1, Sorbonne Univ
  - Damiano Lombardi
    * Mini-course Modeling the electrophysiology of heart, 1.5h, M2, Ecole des Mines Paristech
    * TD, Numerical Methods, M1, 15 h, Sorbonne Univ
    * TP, Numerical Methods, M1, 24 hours, 09/2021, Sorbonne Université.

9.2.2 Supervision

- PhD in progress: Mocia Agbalessi, Modeling and patient specific fluid-structure interaction simulations of aortic pathological configurations. Since April, 2019, Supervisors: M.A. Fernández Varela & D. Lombardi
- PhD in progress: Mathieu Barré, Mathematical and numerical study of a poroelastic model. Supervisors: C. Grandmont & P. Moireau (M3DISIM, Inria Saclay)
- PhD in progress: Marguerite Champion, Modeling, analysis and simulation of fluid-structure-contact interaction. Supervisors: M.A. Fernández Varela, C. Grandmont, F. Vergnet & M. Vidrascu
- PhD in progress: Daniele Corti, Modeling and numerical simulation of the mitral apparatus. Since October 2020. Supervisors: M.A. Fernández Varela, G. Delay , F. Vergnet & M. Vidrascu
- PhD in progress: Sara Costa Faya, An in silico approach to monitor and predict haemodynamics during safety pharmacology studies. Since September 2020. Supervisors: M.A. Fernández Varela, C. Grandmont & D.Lombardi

- PhD in progress: Maria Fuente Ruiz , Adaptive tensor methods for scientific computing. Supervisors: D. Lombardi & V. Ehrlacher
- PhD in progress: Fabien Lespagnol, A new computational approach for fluid-structure interaction of slender bodies immersed in three-dimensional flow. Since September 2020. Supervisors: M. Boulakia, M.A. Fernández Varela, C. Grandmont & Paolo Zunino (MOX, Politechnico de Milano)
- PhD in progress: Haibo Liu, Data assimilation for high-throughput screening in safety pharmacology. Since September 2020. Supervisors: D. Lombardi & M. Boulakia
- PhD in progress: Fabien Raphel, Mathematical modeling and learning of biomedical signals for safety pharmacology. Since April 2019. Supervisors: J.-F. Gerbeau & D. Lombardi
- PhD defended: Felipe Galarce, Enhancing hemodynamics measurements with mathematical modeling. April 2021. Supervisors: J.-F. Gerbeau, D. Lombardi & O. Mula
- PhD defended: Fannie Gerosa, Immersed boundary methods for fluid-structure interaction with topological changes. April 2021. Supervisor: M.A. Fernández Varela
- PostDoc in progress: Mihai Nechita. flow reconstruction from 4D-flow MRI. Supervisors: M. Boulakia & M.A. Fern´andez Varela
- PostDoc in progress: Sebastien Riffaud. Tensor methods for parametric fluid-structure interaction and data assimilation. Supervisors: D. Lombardi & M.A. Fern´andez Varela
- PostDoc in progress: Fréderique Nöel, Modelling of ventilation and gaz diffusion in the contect of Covid disease. Supervisors: C. Grandmont

9.2.3 Juries

- Muriel Boulakia
  - PhD Committee : Amel Karoui, Univ Bordeaux, Mar 2021
- Miguel Ángel Fernández Varela
  - Hiring committees: Inria CRCN Nancy and Inria DR2
  - PHD committee: Alleau Thibaut, UTC (reviewer) Dec 2021
- Céline Grandmont
  - Hiring committees: Inria Saclay (president) and Inria DR2
  - PHD committee:
    - President of the PhD committee of Ladya KHOUN, Sorbonne Univ, Jan 2021
    - Nicolas Barnafi, MOX, Polytechnico de Milano (reviewer), Feb 2021
    - Simone di Gregorio, MOX, Polytechnico de Milano, Feb 2021
    - David Michel, Sorbonne Univ, Jul 2021
    - Liudi Lu Sorbonne Univ, Sep 2021
    - Michael Brunnengo, Univ Côte d'Azur (reviewer), Oct 2021
  - HDR committee: Aline Lefebvre, Ecole Polytechnique (president), Dec 2021
- Damiano Lombardi
  - Hiring committe Inria Paris
- Marina Vidrascu
  - PhD Committee : Xingyi Wang, UTC July 2021

9.3 Popularization

9.3.1 Interventions

- Céline Grandmont
  - Online seminar (2h), at master level, Master "mathématiques pour les sciences de la vie", Université Paris Saclay, march 2021
  - Seminar (2h), at master level "Mathématiques et applications : recherche et interactions" Strasbourg Univ., Nov. 2021
- Damiano Lombardi
  - Demie-heure de science, Inria Paris, 02/2021 *Safety pharmacology and mathematics.*
  - Ncardia, Leiden, seminar for an industrial partner, 11/2021, *On Data Assimilation in biomedical applications.*

10 Scientific production

10.1 Major publications

[1] L. Boudin, C. Grandmont, B. Grec, S. Martin, A. Mecherbet and F. Noël. 'Fluid-kinetic modelling for respiratory aerosols with variable size and temperature'. In: *ESAIM: Proceedings and Surveys* 67 (2020), pp. 100–119. DOI: 10.1051/proc/202067007. URL: https://hal.archives-ouvertes.fr/hal-02092574.

[2] M. Boulakia, E. Burman, M. A. Fernández and C. Voisembert. 'Data assimilation finite element method for the linearized Navier-Stokes equations in the low Reynolds regime'. In: *Inverse Problems* 36.8 (1st May 2020). DOI: 10.1088/1361-6420/ab9161. URL: https://hal.inria.fr/hal-02318504.

[3] V. Ehrlacher, M. Fuente-Ruiz and D. Lombardi. 'SoTT: greedy approximation of a tensor as a sum of Tensor Trains'. In: *SIAM Journal on Scientific Computing* (2021). URL: https://hal.inria.fr/hal-03018646.

[4] F. Galarce, J.-F. Gerbeau, D. Lombardi and O. Mula. 'Fast reconstruction of 3D blood flows from Doppler ultrasound images and reduced models'. In: *Computer Methods in Applied Mechanics and Engineering* (1st Mar. 2021). DOI: 10.1016/j.cma.2020.113559. URL: https://hal.archives-ouvertes.fr/hal-02403686.

[5] C. Grandmont and F. Vergnet. 'Existence and uniqueness for a quasi-static interaction problem between a viscous fluid and an active structure'. In: *Journal of Mathematical Fluid Mechanics* 23.45 (27th Mar. 2021). DOI: 10.1007/s00021-020-00552-0. URL: https://hal.archives-ouvertes.fr/hal-02493384.

[6] N. Pozin, S. Montesantos, I. Katz, M. Pichelin, I. Vignon-Clementel and C. Grandmont. 'Predicted airway obstruction distribution based on dynamical lung ventilation data: a coupled modeling-machine learning methodology'. In: *International Journal for Numerical Methods in Biomedical Engineering* 34.9 (May 2018). DOI: 10.1002/cnm.3108. URL: https://hal.archives-ouvertes.fr/hal-01568065.

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10.2 Publications of the year

International journals

[9] M. Boulakia, M. De Buhan and E. Schwindt. 'Numerical reconstruction based on Carleman estimates of a source term in a reaction-diffusion equation.' In: *ESAIM: Control, Optimisation and Calculus of Variations* (2021). DOI: 10.1051/cocv/2020086. URL: https://hal.archives-ouvertes.fr/hal-02185889.

[10] J.-J. Casanova, C. Grandmont and M. Hillairet. 'On an existence theory for a fluid-beam problem encompassing possible contacts'. In: *Journal de l'École polytechnique — Mathématiques* 8 (11th Mar. 2021), pp. 933–971. URL: https://hal.archives-ouvertes.fr/hal-02396915.

[11] C. Dupont, M. Vidrascu, P. Le Tallec, D. Barthès-Biesel and A.-V. Salsac. 'Modelling the fluid-structure interactions of a capsule using a nonlinear thin shell model: effect of wall thickness'. In: *Journal of Fluids and Structures* (2021). URL: https://hal.utc.fr/hal-03409766.

[12] V. Ehrlacher, M. Fuente-Ruiz and D. Lombardi. 'SoTT: greedy approximation of a tensor as a sum of Tensor Trains'. In: *SIAM Journal on Scientific Computing* (2021). URL: https://hal.inria.fr/hal-03018646.

[13] V. Ehrlacher, L. Grigori, D. Lombardi and H. Song. 'Adaptive hierarchical subtensor partitioning for tensor compression'. In: *SIAM Journal on Scientific Computing* (2021). DOI: 10.1137/19M128689X. URL: https://hal.inria.fr/hal-02284456.

[14] S. Frei, F. Gerosa, E. Burman and M. A. Fernández. 'A mechanically consistent model for fluid-structure interactions with contact including seepage'. In: *Computer Methods in Applied Mechanics and Engineering* (2022). URL: https://hal.archives-ouvertes.fr/hal-03174087.

[15] F. Galarce, J.-F. Gerbeau, D. Lombardi and O. Mula. 'Fast reconstruction of 3D blood flows from Doppler ultrasound images and reduced models'. In: *Computer Methods in Applied Mechanics and Engineering* (1st Mar. 2021). DOI: 10.1016/j.cma.2020.113559. URL: https://hal.archives-ouvertes.fr/hal-02403686.

[16] C. Grandmont and S. Martin. 'Existence of solutions and continuous and semi-discrete stability estimates for 3D/0D coupled systems modelling airflows and blood flows'. In: *ESAIM: Mathematical Modelling and Numerical Analysis* 55.5 (Sept. 2021), pp. 2365–2419. DOI: 10.1051/m2an/2021055. URL: https://hal.archives-ouvertes.fr/hal-03393268.

[17] C. Grandmont and F. Vergnet. 'Existence and uniqueness for a quasi-static interaction problem between a viscous fluid and an active structure'. In: *Journal of Mathematical Fluid Mechanics* 23.45 (27th Mar. 2021). DOI: 10.1007/s00021-020-00552-0. URL: https://hal.archives-ouvertes.fr/hal-02493384.

[18] D. Lombardi and F. Raphel. 'A method to enrich experimental datasets by means of numerical simulations in view of classification tasks'. In: *ESAIM: Mathematical Modelling and Numerical Analysis* 55.5 (Sept. 2021), pp. 2259–2291. DOI: 10.1051/m2an/2021060. URL: https://hal.archives-ouvertes.fr/hal-03377036.

Doctoral dissertations and habilitation theses

[19] F. Galarce Marin. 'Inverse problems in hemodynamics. Fast estimation of blood flows from medical data'. Inria Paris; Sorbonne Universite; Laboratoire Jacques-Louis Lions, 9th Apr. 2021. URL: https://hal.archives-ouvertes.fr/tel-03221563.

[20] F. M. Gerosa. 'Immersed boundary methods for fluid-structure interaction with topological changes'. Sorbonne Université, 13th Apr. 2021. URL: https://tel.archives-ouvertes.fr/tel-03240631.

Reports & preprints

[21] M. Agbalessi, A. Lalande, O. Bouchot, T. Hayase, J.-J. Christophe, M. A. Fernández and D. Lombardi. *Reconstruction of the Lagrangian deformation of the aorta from 4D MRI data*. 20th Sept. 2021. URL: https://hal.inria.fr/hal-03349442.

[22] A. Aggarwal, D. Lombardi and S. Pant. *An information-theoretic framework for optimal design: analysis of protocols for estimating soft tissue parameters in biaxial experiments*. 31st Mar. 2021. URL: https://hal.inria.fr/hal-03187110.

[23] H. Al Daas and D. Lombardi. *An extended Krylov-like method for the solution of multi-linear systems*. 12th Oct. 2021. URL: https://hal.inria.fr/hal-03374966.

[24] M. Barré, C. Grandmont and P. Moireau. *Analysis of a linearized poromechanics model for incompressible and nearly incompressible materials*. 23rd Dec. 2021. URL: https://hal.inria.fr/hal-03501526.

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[26] E. Burman, R. Durst, M. A. Fernández and J. Guzmán. *Loosely coupled, non-iterative time-splitting scheme based on Robin-Robin coupling: Unified analysis for Parabolic/Parabolic and Parabolic/Hyperbolic problems*. 17th Oct. 2021. URL: https://hal.archives-ouvertes.fr/hal-03381765.

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[29] F. Galarce, D. Lombardi and O. Mula. *State Estimation with Model Reduction and Shape Variability. Application to biomedical problems*. 18th June 2021. URL: https://hal.inria.fr/hal-03264205.

[30] D. Lombardi. *Fast state estimation in nonlinear parametric time dependent systems using Tensor Train*. 13th Oct. 2021. URL: https://hal.inria.fr/hal-03375811.

10.3 Cited publications

[31] F. Alauzet, B. Fabrèges, M. A. Fernández and M. Landajuela. 'Nitsche-XFEM for the coupling of an incompressible fluid with immersed thin-walled structures'. In: *Comput. Methods Appl. Mech. Engrg.* 301 (2016), pp. 300–335.

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[36] D. Boffi, N. Cavallini and L. Gastaldi. 'Finite element approach to immersed boundary method with different fluid and solid densities'. In: *Math. Models Methods Appl. Sci.* 21.12 (2011), pp. 2523–2550.

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[38] L. Boudin, D. Götz and B. Grec. 'Diffusion models of multicomponent mixtures in the lung'. In: *CEMRACS 2009: Mathematical modelling in medicine*. Vol. 30. ESAIM Proc. EDP Sci., Les Ulis, 2010, pp. 90–103.

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[40] L. Breiman. *Classification and regression trees*. Routledge, 2017.

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[44] P. Cazeaux and C. Grandmont. 'Homogenization of a multiscale viscoelastic model with nonlocal damping, application to the human lungs'. In: *Math. Models Methods Appl. Sci.* 25.6 (2015), pp. 1125–1177.

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