Activity Report 2012

Project-Team MACS

Modeling, analysis and control in computational structural dynamics

RESEARCH CENTER
Saclay - Île-de-France

THEME
Observation, Modeling, and Control for Life Sciences

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Project-Team MACS

Keywords: Scientific Computation, Finite Elements, Data Assimilation, Inverse Problem, Virtual Physiology, Fluid-structure Interaction

Creation of the Project-Team: February 01, 2000 .

1. Members

Research Scientists
Dominique Chapelle [Team Leader DR, HdR]
Philippe Moireau [on secondment from “Corps des Mines”]

Engineers
Marc Fragu [till October]
Sébastien Gilles [beginning November]

PhD Students
Annabelle Collin
Alexandre Imperiale
Daniele Trimarchi [till May]

Post-Doctoral Fellows
Matthieu Caruel
Karine Mauffrey [beginning September]

2. Overall Objectives

2.1. Introduction

Numerical simulation has become a widespread tool in engineering. This fact is particularly noteworthy in the field of solid and structural mechanics which has given birth to finite element methods. In industrial design processes, experimenting and simulation go hand in hand, but the balance is increasingly shifted towards simulation, resulting into reduced costs and time to market.

In this general context, the objectives of the Macs project are to address new challenges arising from:

- the need to develop numerical procedures which are *reliable* and well-adapted to *industrial applications*;
- the emergence of *active mechanics* (e.g. control and optimisation) enabling the design of thinner and lighter (hence cheaper) structures, for which innovative modeling and discretization approaches are required.

These research directions benefit from a strong scientific environment and background at Inria in the fields of numerical analysis and scientific computing (with a well-established record in structural mechanics), as well as in automatic control.

We also emphasize that – in the past five years – we have increasingly investigated specific topics pertaining to biomechanical modeling.

2.2. Highlights of the Year

The team has relocated from Rocquencourt to the Saclay Ile-de-France Inria research center in June 2012. This change was motivated by the very strong potential of this rapidly-evolving environment in terms of multi-disciplinary collaborations, with the actors already in place as well as those to come, in particular with the creation of the ambitious new Paris-Saclay University. We are already part of a local initiative entitled “Mechanics and living systems” in association with various components of the two mechanics laboratories of Ecole Polytechnique, and which encompasses fundamental, experimental and numerical aspects in biomechanics. This environment is also foreseen as most favorable to the launching of our successor-team, since 2012 was the last year of the Macs team itself, indeed.

3. Scientific Foundations

3.1. Formulation and analysis of effective and reliable shell elements

Thin structures (beams, plates, shells...) are widely considered in engineering applications. However, most experts agree that the corresponding discretization procedures (finite elements) are not yet sufficiently reliable, in particular as regards shell structures. A major cause of these difficulties lies in the numerical locking phenomena that arise in such formulations [2].

The expertise of the team in this area is internationally well-recognized, both in the mathematical and engineering communities. In particular, we have strongly contributed in analysing – and better explaining – the complex locking phenomena that arise in shell formulations [2]. In addition, we have proposed the first (and only to date) shell finite element procedure that circumvents locking [6]. However, the specific treatment applied to avoid locking in this procedure make it unable to correctly represent membrane-dominated behaviors of structures (namely, when locking is not to be expected). In fact, a “perfect shell element” – namely, with the desired reliability properties mathematically substantiated in a general framework – is still to be discovered, whereas numerous teams work on this issue throughout the world.

Another important (and related) issue that is considered in the team pertains to the design and analysis of numerical procedures that are adapted to industrial applications, i.e. that fulfill some actual industrial specifications. In particular, in the past we have achieved the first mathematical analysis of “general shell elements” – which are based on 3D variational formulations instead of shell models – these elements being among the most widely used and most effective shell elements in engineering practice.

3.2. Stability and control of structures

Stability of structures is – of course – a major concern for designers, in particular to ensure that a structure will not undergo poorly damped (or even unbounded) vibrations. In order to obtain improved stability properties – or to reach nominal specifications with a thinner a lighter design – a control device (whether active, semi-active, or passive) may be used.

The research performed in the team in this area – other than some prospective work on robust control – has been so far primarily focused on the stability of structures interacting with fluid flows. This problem has important applications e.g. in aeronautics (flutter of airplane wings), in civil engineering where the design of long-span bridges is now partly governed by wind effects, and in biomechanics (blood flows in arteries, for instance). Very roughly, the coupling between the structure and the flow can be described as follows: the structural displacements modify the geometry of the fluid domain, hence the fluid flow itself which in turn exerts an action on the structure. The effects of structural displacements on the fluid can be taken into account using ALE techniques, but the corresponding direct simulations are highly CPU-intensive, which makes stability analyses of such coupled problems very costly from a computational point of view. In this context a major objective of our work has been to formulate a simplified model of the fluid-structure interaction problem in order to allow computational assessments of stability at a reasonable cost.

3.3. Modeling and estimation in biomechanics

A keen interest in questions arising from the need to model biomechanical systems – and to discretize such problems – has always been present in the team since its creation. Our work in this field until now has been more specifically focused on the objectives related to our participation in the ICEMA ARC projects and in the CardioSense3D initiative, namely, to formulate a complete continuum mechanics model of a beating heart, and to confront – or "couple", in the terminology of the Inria strategic plan – numerical simulations of the model with actual clinical data via a data assimilation procedure.

Our global approach in this framework thus aims at using measurements of the cardiac activity in order to identify the parameters and state of a global electromechanical heart model, hence to give access to quantities of interest for diagnosing electrical activation and mechanical contraction symptoms. The model we propose is based on a chemically-controlled constitutive law of cardiac myofibre mechanics consistent with the behavior of myosin molecular motors [27]. The resulting sarcomere dynamics is in agreement with the "sliding filament hypothesis" introduced by Huxley. This constitutive law has an electrical quantity as an input which can be independently modeled, considered as given (or measured) data, or as a parameter to be estimated.

4. Application Domains

4.1. Application domains

Our researches have natural applications in all sectors of the mechanical industry: car and naval industries; aeronautics and space; civil engineering; tires; MEMs and nanotechnologies...

We also actively seek new applications in biotechnologies, although of course the economy and structuring of this sector is not as developed yet.

5. Software

5.1. FELISCE

Participants: Dominique Chapelle, Sébastien Gilles [correspondant], Philippe Moireau.

FELISCE – standing for "Finite Elements for LIfe SCiences and Engineering" – is a new finite element code which the MACS and REO teams have decided to 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 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. https://gforge.inria.fr/projects/felisce/

5.2. HeartLab

Participants: Matthieu Caruel, Dominique Chapelle, Alexandre Imperiale, Philippe Moireau [correspondant].

The heartLab software is a library written in (64 bits compatible) Matlab and C (mex functions) designed to perform both simulation and estimation (based on various types of measurements, e.g. images) of the heart mechanical behavior. Started in 2006, it is already quite large (about 60,000 lines), and is used within the CardioSense3D community.

The code relies on OpenFEM for the finite element computations, and the implementation was performed with a particular concern for modularity, since modeling and estimation use the same finite element operators. This modularity also allows to couple the code with other FEM solvers, such as LifeV and Mistral developed in the Reo team-project. In particular, we are now able to include perfusion and electrical coupling with LifeV using PVM, and fluid-structure interaction using Mistral.

We also included geometric data and tools in the code to define heart anatomical models compatible with the simulation requirements in terms of mesh quality, fiber direction data defined within each element, and referencing necessary for handling boundary conditions and estimation, in particular. These geometries are analytical or come from computerized tomography (CT) or magnetic resonance (MR) image data of humans or animals.

We recently incorporated numerous non-linear data assimilation observation operators based on medical imaging post-processing to be able to now perform estimation with a large variety of medical imaging modalities.

5.3. MITCNL

Participants: Dominique Chapelle [correspondant], Marina Vidrascu [REO team].

The package MITCNL is a set of subroutines that implements the triangular MITC3, MITC6 and quadrilateral MITC4 and MITC9 shell elements for large displacements [2]. We use it as a basis for new developments of shell elements, in particular within Modulef (http://www-rocq.inria.fr/modulef/). It can be easily interfaced with most finite element codes as well. We also license this package to some of our partners for use with their own codes.

5.4. OpenFEM: a Finite Element Toolbox for Matlab and Scilab

Participants: Dominique Chapelle, Philippe Moireau [correspondant].

OpenFEM (http://www.openfem.net) is an *opensource* finite element toolbox for linear and nonlinear structural mechanics within the Matlab and Scilab matrix computing environments. This software is developed in a collaboration between Macs and the SDTools company [1]. Performing finite element analyses within a matrix computing environment is of considerable interest, in particular as regards the ease of new developments, integration of external software, portability, post-processing, etc.

This Library is the core of the finite element computations of HeartLab where a specific version have been developed with the help of Cesare Corrado from Reo.

5.5. SHELDDON

Participants: Dominique Chapelle [correspondant], Marina Vidrascu [REO team].

SHELDDON (SHELls and structural Dynamics with DOmain decomposition in Nonlinear analysis) is a finite element library based on the Modulef package which contains shell elements, nonlinear procedures and PVM subroutines used in domain decomposition or coupling methods.

5.6. Verdandi

Participants: Dominique Chapelle, Marc Fragu, Vivien Mallet [Clime team], Philippe Moireau [correspondant].

Verdandi is an opensource (LGPL) software library aiming at providing assimilation data methods and related tools. Mainly targeted at large systems arising from the discretization of PDEs, it is intentionally devised as generic, which allows for applications in a wide range of problems (biology and medicine, environment, image processing...). See also the web page http://verdandi.gforge.inria.fr/, with a complete documentation in English. The first stable version (1.0) was released in June 2012 and contains most of the major data assimilation algorithms of both variational and sequential types. The actual version (1.4) contains additional estimation algorithm and parallel capabilities. Note that some specific developments are performed with particular regard to cardiac modeling applications, as Verdandi is partly funded by – and distributed within – the euHeart project and is now referenced in the following peer-reviewed article [15]

- ACM: Mathematical software

[1] http://www.sdtools.com

- AMS: System theory; control
- Software benefit: Verdandi is the only *generic* data assimilation library
- License: LGPL (2.1 or any later version)
- Type of human computer interaction: Command line and configuration files
- OS/Middelware: Linux, MacOS ou Windows
- Required library or software: Seldon (LGPL, http://seldon.sourceforge.net/)
- Programming language: C++, ISO/IEC 14882: I998(E) Python, version 2.6
- Documentation: Doxygen and utilisation manual in english

6. New Results

6.1. Asymptotic and multiscale modeling in biomechanics

6.1.1. Detailed validations of muscle model

Participants: Matthieu Caruel, Dominique Chapelle, Alexandre Imperiale, Philippe Moireau.

Until recently we had only considered simple isotropic passive laws of Mooney-Rivlin type in our muscle model, albeit with an overall behavior already highly non-isotropic due to the fiber-oriented active component. We have now implemented and calibrated a new visco-hyperelastic passive law of exponential and orthotropic type for the hyperelastic part, in better agreement with the models and data generally found in the literature. It should be noted that most experimental data available concern the passive behavior only, indeed. In addition, we implemented a new conservative numerical scheme for the time discretization of the contractile variables. Moreover an original boundary condition of contact type has been successfully applied on several detailed cardiac geometries to represent the interactions between the epicardium, pericardium and the surrounding structures.

Major advances in the understanding of heart contraction cycle can be achieved by testing papillary muscle preparations *in vitro*. Single papillary muscles have an essentially one-dimensional structure suitable for uniaxial mechanical testing, and therefore represent the simplest setup to test the robustness of a model of heart contraction against a vast set of experimental results available in the literature. In collaboration with Y. Lecarpentier (Institut du Coeur, Pitié-Salpêtrière Hospital, Paris) and R. Chabiniok (King's College London), we have further refined and calibrated the muscle mechanical model in order to quantitatively reproduce experimental data from rat cardiomyocytes. These results include the static stress-strain constitutive relation, kinetic response to isotonic loadings, and force-velocity relation see Fig.1.

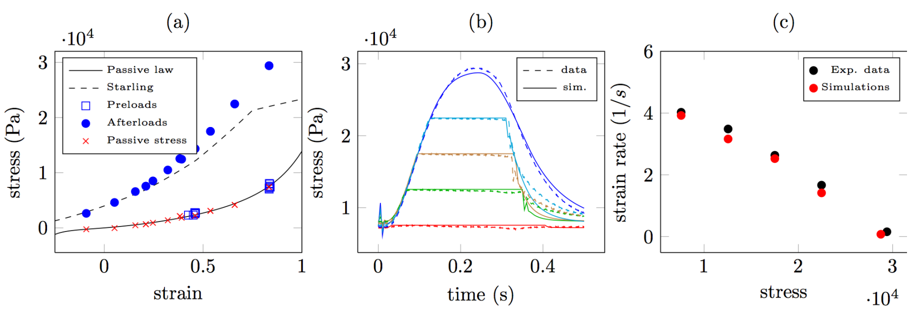

Figure 1. Results of the model compared with experimental data

6.1.2. Multi-scale mechanics of muscle contraction

Participant: Matthieu Caruel.

Muscles are an active tissue material capable of producing force. At the microscale, force is the result of complex interactions between two types of proteins, namely, actin and myosin, which work coherently in very large assemblies ($\sim 10^9$). The passive mechanical response of so-called striated muscles at fast time scales is dominated by long range interactions inducing cooperative behavior without breaking the detailed balance. This leads to such unusual material properties as negative equilibrium stiffness and drastically different behavior in force and displacement controlled loading conditions. Analysing experimental data strongly suggests that muscles are finely tuned to perform close to a critical point (see Fig.2). This work in collaboration with Jean-Marc Allain and Lev Truskinovsky (LMS, Ecole Polytechnique) is the subject of a paper submitted to Physical Review Letters (see [22]).

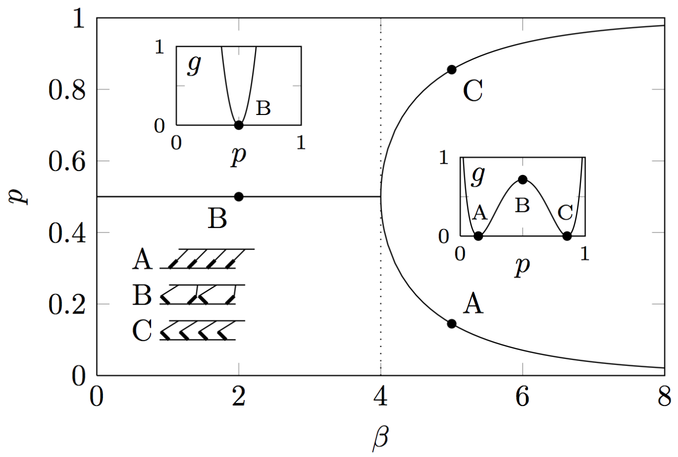

Figure 2. Bifurcation diagram of a model of coupled molecular motors. p is the fraction of motors in the stress generating configuration (post-power-stroke). β is a non dimensional parameter representing the intensity of thermal fluctuations ($\beta \to 0$ represents infinitely strong thermal forces). For $\beta < 4$, the system lives in a mixed configuration (B): the free energy is convex with a minimum at $p = 1/2$ (see the left inset showing the energy landscape g). For $\beta > 4$ the system is organized in two distinct populations (A and C) corresponding to the 2 minima of a non-convex energy landscape (see the right inset). One population is mainly pre-power-stroke (A) while the other is post-power-stroke (C). This is a signature of mechanical cooperativity.

6.1.3. Asymptotic analysis applied to cardiac electrophysiology modeling

Participants: Dominique Chapelle, Annabelle Collin, Jean-Frédéric Gerbeau [(REO team)].

Computational electrophysiology is a very active field with tremendous potential in medical applications, albeit leads to highly intensive simulations. We here propose a surface-based electrophysiology formulation, motivated by the modeling of thin structures such as cardiac atria, which greatly reduces the size of the computational models. Moreover, our model is specifically devised to retain the key features associated with the anisotropy in the diffusion effects induced by the fiber architecture, with rapid variations across the thickness which cannot be adequately represented by naive averaging strategies. Our proposed model relies on a detailed asymptotic analysis in which we identify a limit model and establish strong convergence results. We also provide detailed numerical assessments which confirm an excellent accuracy of the surface-based model – compared with the reference 3D model – including in the representation of a complex phenomenon, namely, spiral waves, see Figure 3. This work was submitted for publication in "M3AS: Mathematical Models and Methods in Applied Sciences".

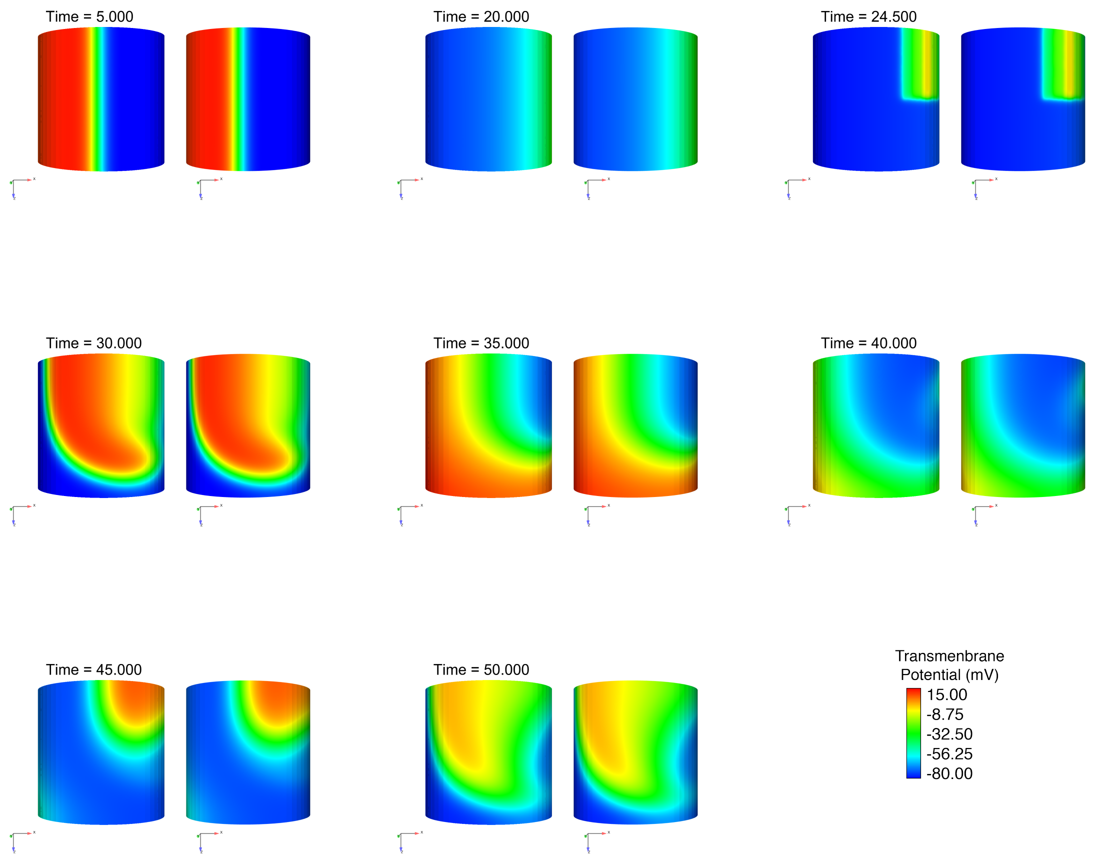

Figure 3. Spiral wave on cylinder – Comparison of asymptotic surface model (left), 3D model (center) and naive 2D model (right) on the midsurface at 8 consecutive times

6.1.4. Cardiac atria electrophysiology surface-based modeling and assessment of physiological simulations

Participants: Dominique Chapelle, Annabelle Collin, Jean-Frédéric Gerbeau [(REO team)].

We aim at validating the 2D (namely, surface-based) electrophysiology model designed for thin cardiac structures with strongly heterogeneous anisotropy, presented in Paragraph 6.1.3 with a real model of the atria. We produced a surface mesh representing the mid-surface of the two atria. We used the bibliography to identify and prescribe the fibers directions at the endocardium and epicardium. Figure 4 displays the simulation results obtained with the surface-based model.

6.1.5. Strong convergence results in the asymptotic behavior of the 3D-shell model

Participants: Dominique Chapelle, Annabelle Collin.

The objective of this work is to establish the strong convergence for the asymptotic analysis of the so-called 3D-shell model presented in [2]. We apply similar methods to those used in the work on "Asymptotic analysis applied to cardiac electrophysiology modeling".

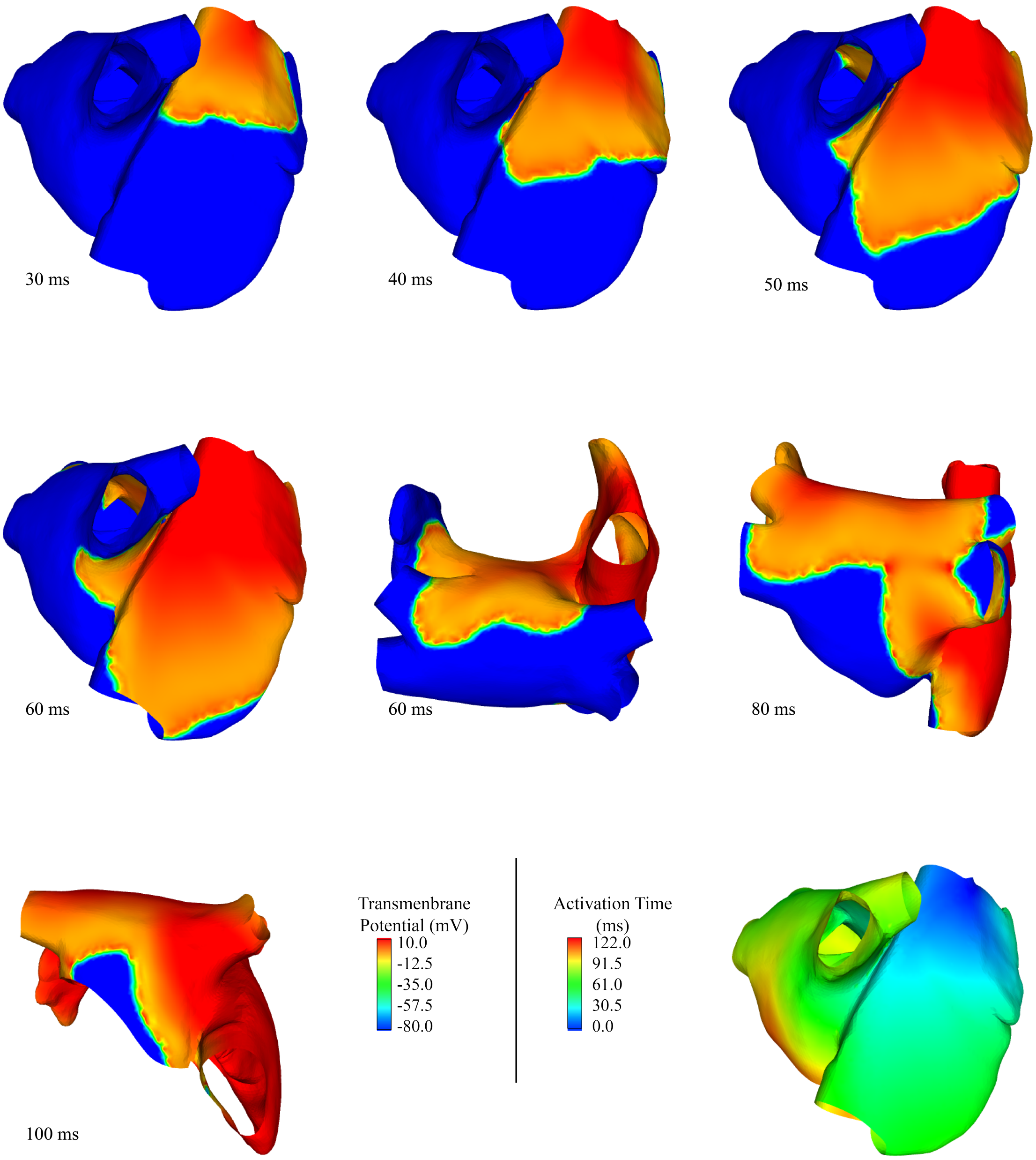

Figure 4. Simulation of atrial depolarization

6.2. Estimation in biomechanics

6.2.1. Exponential convergence of an observer based on partial field measurements for the wave equation

Participants: Dominique Chapelle, Philippe Moireau.

We analyze an observer strategy based on partial—that is, in a subdomain—measurements of the solution of a wave equation, in order to compensate for uncertain initial conditions. We prove the exponential convergence of this observer under a nonstandard observability condition, whereas using measurements of the time derivative of the solution would lead to a standard observability condition arising in stabilization and exact controllability. Nevertheless, we directly relate our specific observability condition to the classical geometric control condition. Finally, we provide some numerical illustrations of the effectiveness of the approach. This work in collaboration with M. de Buhan (Univ. Paris V) and N. Cîndea (Univ. Clermont-Ferrand) is published in [13].

6.2.2. Sequential identification of boundary support parameters in a fluid-structure vascular model using patient image data

Participants: Dominique Chapelle, Philippe Moireau.

This work [17] is in collaboration with C. Bertoglio and J.-F. Gerbeau (REO team) and N. Xiao, C.A. Figueroa and C.A. Taylor (Stanford University), where we propose a complete methodological chain for the identification of the corresponding boundary support parameters, using patient image data. We consider distance maps of model to image contours as the discrepancy driving the data assimilation approach, which then relies on a combination of (1) state estimation based on the so-called SDF filtering method, designed within the realm of Luenberger observers and well-adapted to handling measurements provided by image sequences, and (2) parameter estimation based on a reduced-order UKF filtering method which has no need for tangent operator computations and features natural parallelism to a high degree. Implementation issues are discussed, and we show that the resulting computational effectiveness of the complete estimation chain is comparable to that of a direct simulation. Furthermore, we demonstrate the use of this framework in a realistic application case involving hemodynamics in the thoracic aorta. The estimation of the boundary support parameters proves successful, in particular in that direct modeling simulations based on the estimated parameters are more accurate than with a previous manual expert calibration. This paves the way for complete patient-specific fluid-structure vascular modeling in which all types of available measurements could be used to estimate additional uncertain parameters of biophysical and clinical relevance.

This work published in BMMB (impact factor 3.192) can be considered as the first trial of data assimilation using real data in hemodynamics.

6.2.3. Filtering strategies using image data

Participants: Alexandre Imperiale, Philippe Moireau, Alexandre Routier.

Some progress has been achieved concerning the Luenberger filtering procedure – also known as nudging – for the cardiovascular system in several directions. We have studied the impact of data interpolation (in time and space) on the method performance (a paper on this subject is being prepared) and, during Alexandre Routier end-of-curriculum internship from INSA Rouen, we have adapted the formalism of currents (inspired by a collaboration with S. Durrleman). This formalism in an elegant way to represent geometric objects (endo- and epicardium surfaces for example) as operators on a test vector space defined on the ambient space. From this key idea the main work was to define a numerical tractable norm on the space of surfaces and derive it with respect to the Lagrangian displacement of the solid domain in order to incorporate such a representation of surfaces into our filtering technique. Among other advantages this new observer requires significantly less prior efforts in terms of image processing.

6.2.4. Formulation of observers for parabolic equations

Participants: Karine Mauffrey, Philippe Moireau.

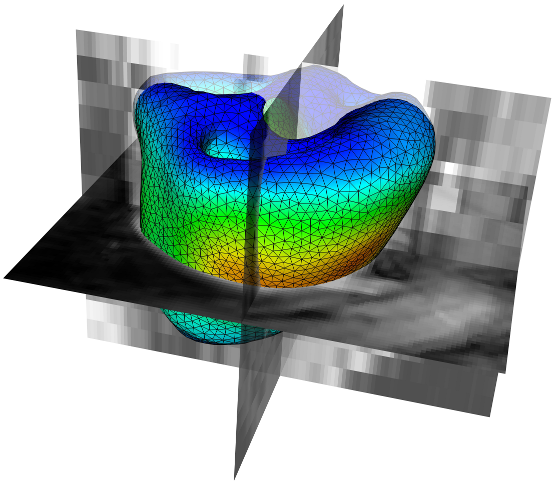

Figure 5. Results of the model compared with experimental data

We are currently working on optimal filtering using observers for a class of evolution PDEs including heat-like equations. As for the optimal control issue,the optimal filtering issue is related to the resolution of a differential Riccati equation. In [25] or [29], the link between the optimal filtering formulations and the derived Riccati equation is done by finite dimension arguments. There exist also other results on the linear quadratic optimal control that are based on infinite dimensional considerations (see, for example, [26] and [28]). A work in progress consists in presenting a direct approach for the optimal filtering issue, using infinite dimension considerations only. Then we should be able to introduce reduced-rank considerations to be able to stabilize only the low frequencies part of the parabolic system, and therefore offer a discretization strategy. This discretization will the be analyzed in details.

6.3. Other topics

6.3.1. Sail modeling

Participants: Dominique Chapelle, Daniele Trimarchi.

This is a collaboration with Marina Vidrascu (REO team) and Stephen Turnock and Dominic Taunton (Southampton University), as part of the recently completed PhD of Daniele Trimarchi. We propose a method of modelling sail type structures which captures the wrinkling behaviour of such structures. The method is validated through experimental and analytical test cases, particularly in terms of wrinkling prediction. An enhanced wrinkling index is proposed as a valuable measure characterizing the global wrinkling development on the deformed structure. The method is based on a pseudo-dynamic finite element procedure involving non-linear MITC shell elements. The major advantage compared to membrane models generally used for this type of analysis is that no ad hoc wrinkling model is required to control the stability of the structure. We demonstrate our approach to analyse the behaviour of various structures with spherical and cylindrical shapes, characteristic of downwind sails over a rather wide range of shape and constitutive parameters. In all cases convergence is reached and the overall flying shape is most adequately represented, which shows that our approach is a most valuable alternative to standard techniques to provide deeper insight into the physical behaviour. Limitations appear only in some very special instances in which local wrinkling-related instabilities are extremely high and would require specific additional treatments, out of the scope of the present study. This work has been published in [20].

6.3.2. PODs for parameter-dependent problems and estimation

Participants: Dominique Chapelle, Philippe Moireau.

This work – submitted to M2AN [24] – is derived from the latest part of Asven Gariah's PhD, jointly supervised by Jacques Sainte-Marie (Bang team) and D. Chapelle, and defended in late 2011. We address the issue of parameter variations in POD approximations of time-dependent problems, without any specific restriction on the form of parameter dependence. Considering a parabolic model problem, we propose a POD construction strategy allowing us to obtain some *a priori* error estimates controlled by the POD remainder – in the construction procedure – and some parameter-wise interpolation errors for the model solutions. We provide a thorough numerical assessment of this strategy with the FitzHugh-Nagumo 1D model. Finally, we give detailed illustrations of the approach in two parameter estimation applications, the first in a variational estimation framework with the FitzHugh-Nagumo model, and the second with a beating heart mechanical model for which we employ a sequential estimation method to characterize model parameters using real image data in a clinical case.

7. Partnerships and Cooperations

7.1. European Initiatives

7.1.1. FP7 Projects

7.1.1.1. EUHEART

Title: euHeart

Type: COOPERATION (ICT)

Defi: Virtual Physiological Man

Instrument: Integrated Project (IP)

Duration: June 2008 - May 2012

Coordinator: Philips Technologie GmbH Forschungslaboratorien (Germany)

Others partners: Philips Technologie GmbH (DE), The University of Oxford (UK), Universitat Pompeu Fabra (SP), The University of Sheffield (UK), Inria, French National Research Institute in Informatics and Mathematics (FR), King's College London (UK), Academisch Medisch Centrum bij de Universiteit van Amsterdam (NL), Universität Karlsruhe (TH) (DE), Institut National de la Santé et de la Recherche Médicale, INSERM (FR), Philips Medical Systems Nederland BV (NL), Berlin Heart GmbH (DE), HemoLab BV (NL), Universitätsklinikum Heidelberg (DE), Volcano Europe SA / NV (BE), Hospital Clínico San Carlos de Madrid (SP), Philips Ibérica S.A. (SP)

See also: http://www.euheart.eu/

Abstract: The euHeart project (Ref 224495), is a 4-year integrated European project which aims at developing personalized, and clinically validated multi-physics, multi-level models of the heart and great vessels. Those models need to be tightly integrated with signal and image processing tools in order to assist clinical decision making and to help reducing morbidity and mortality rates associated with cardiovascular diseases. Asclepios is leading a workpackage on radiofrequency ablation for which electromechanical models of the heart are used to improve the planning of radiofrequency ablation lines for patient suffering from atrial fibrillation and ventricular tachycardia.

7.1.1.2. VPH-Share

Title: VPH-Share

Type: COOPERATION (ICT)

Defi: Virtual Physiological Human : Sharing for Healthcare

Instrument: Integrated Project (IP)

Duration: March 2011 - February 2015

Coordinator: Univ. Sheffield (UK)

Others partners: Cyfronet (Cracow), University College London, Istituto Ortopedico Rizzoli (Bologna), NHS, IBM Israel, Univ. Auckland, Agència d'Informació, Avaluació i Qualitat en Salut (Barcelona), Biocomputing Competence Centre (Milano), Universitat Pompeu Fabra (Barcelona), Philips Research, TUE (Eindhoven), Sheffield Teaching Hospitals, Atos Origin (Madrid), the Open University (UK), Univ. Vienna, King's College London, Empirica (Bonn), Fundació Clínic (Barcelona), Univ. Amsterdam

See also: http://vph-share.org/

Abstract: VPH-Share aims at developing the organisational fabric (the infostructure) and integrate the optimised services to expose and share data and knowledge, to jointly develop multiscale models for the composition of new VPH workflows, and to facilitate collaborations within the VPH community. Within this project, the Macs team is in charge of developing some high-performance data assimilation software tools.

7.2. International Initiatives

7.2.1. Inria Associate Teams

7.2.1.1. CARDIO

Title: Mathematical modelling and Numerical Simulation for Cardiovascular Applications

Inria principal investigator: Philippe Moireau

International Partner (Institution - Laboratory - Researcher):

University of California San Diego (United States) - Mechanical and Aerospace Engineering - Alison MARSDEN

Duration: 2008 - 2013

See also: https://idal.inria.fr/cardio/

To improve disease understanding, surgical repair or medical device design, mathematical and numerical tools have been the subject of much efforts over the last decades. In this context, we propose a research subject on cardiovascular and air flow modeling. It extends the project of the previous associated team on blood flow modeling to flow of air in the lungs. The goal is to continue to work on bringing together methods developed in the different teams, to compare them if necessary, and to apply them to in-vivo (animal or human) physiologically relevant situations. All the different team members have a strong will to work close to the applications. They all have links to clinicians or biologists, which drive the concrete applications that will be studied: congenital heart disease pathophysiology and repair, artery wall compliance study in normal and pathophysiological cases, heart valve pathophysiology assessment, aerosol deposition in the lungs. Furthermore, the associated team facilitates the breadth of researcher knowledge by exposure to different ways of thinking, methods and/or applications, and by the training of students as they interact with the other institutes.

8. Dissemination

8.1. Scientific Animation

Dominique Chapelle

- Associate editor of international journals Computers & Structures and M2AN
- Guest editor-in-chief (with J.-F. Gerbeau) for M2AN special issue “Direct and inverse modeling of the cardiovascular and respiratory systems”
- Frequent reviewer for journals Computer Methods in Applied Mechanics and Engineering, IJNME
- Program committee of conference “Functional Imaging and Modeling of the Heart 2013”
- Invited lecturer at Mayneord-Phillips Summer School (Oxford, 2–6 July 2012)
- Invited seminars at ETH-Zürich 17/10, CMAP (Ecole Polytechnique) 13 Nov.

Philippe Moireau

- Reviewer this year for M2AN BMMB and EJSOL journals and the American Control Conference
- Project expert reviewer this year for the ANR and the Region Aquitaine
- Invited lecturer at Mayneord-Phillips Summer School (Oxford, 2–6 July 2012) on “Parameter calibration and identification for the cardiovascular system”
- Invited lecturer at Medisys Lab - Philips Research Seminar on “Joint state-parameter estimation for PDEs by observer and optimal filtering strategies”
- Speaker at “PICOF 2012” Conference on “Improving Numerical Analysis Using Observers - the Second-Order Hyperbolic Case”

Alexandre Imperiale

- Speaker at “CANUM 2012” Conference on “Numerical convergence of semi-discrete time and space under-sampled observers for vibrating systems. Application to the wave equation”, May 2012
- Speaker at Medisys Lab - Philips Research Seminar on “Methodological framework for estimation in a cardiac model using tagged-MR images”, July 2012
- Speaker at Inria-Rocquencourt Junior Seminar on “Concepts of data assimilation in cardiac modeling”, April 2012

Annabelle Collin

- Poster at “CANUM 2012” Conference on “A surface-based electrophysiological model motivated by cardiac atria modeling and relying on asymptotic considerations”, May 2012
- Speaker at Junior Seminar Marne-La-Vallée on “A surface-based electrophysiology model relying on asymptotic analysis with physiological simulations”, November 2012

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

Philippe Moireau

Bachelor degree: “MA103 - Introduction aux EDP et à leur approximation numérique”, 14h, M1, ENSTA ParisTech, France

Master: “MA201 - La méthode des éléments finis”, 14h, M2, ENSTA ParisTech, France

Annabelle Collin

Bachelor degre: "Sequences, series, integration" , UPMC, spring 2012

Bachelor degree: "Linear algebra", UPMC, fall 2012

8.2.2. Supervision

PhD & HdR :

Master internship: Alexandre Routier, “Image-based observation operators for data assimilation in cardio-mechanics using currents”, INSA Rouen, june-october 2012, Advisors: A. Imperiale and P. Moireau

Master internship: Silvia Rosellini, “Towards a finite element mesh of a complete human heart”, Pisa University, june-october 2012, Advisor: A. Collin

PhD in progress: Annabelle Collin, “Dimensional reduction and electro-mechanical coupling for the modeling of electrophysiology and muscle contraction”, UPMC, started September 2011, advisors D. Chapelle and J.-F. Gerbeau

PhD in progress: Alexandre Imperiale, “Image-based observation operators for data assimilation in cardio-mechanics”, UPMC, started October 2010, advisors D. Chapelle and P. Moireau

PhD defended in May: Daniele Trimarchi, “Analysis of downwind sail structures using non-linear shells finite elements – Wrinkle development and fluid interaction effects”, University of Southampton, co-supervision D. Chapelle

8.2.3. Juries

Dominique Chapelle

- Thesis committee chairman: R. Sheshka, Ecole Polytechnique, 21 Sept.
- Thesis committee: D. Lopez, Ecole Polytechnique, 15 Oct.
- Thesis committee: C. Bertoglio, UPMC, 23 Nov.

8.3. Popularization

Dominique Chapelle

- Participation to an interview on “la Météo du Coeur” for new site inriality
- Speaker in “Débat citoyen” (Inria-Saclay, 19/11)
- Participation in “Rencontre Inria Industrie” on numerical simulation for medicine (Strasbourg, 21/11)

Philippe Moireau

- Participation to an interview on “la Météo du Coeur” for new site inriality

Annabelle Collin

- Best Poster Award at “CANUM 2012” Conference on “A surface-based electrophysiological model motivated by cardiac atria modeling and relying on asymptotic considerations”

9. Bibliography

Major publications by the team in recent years

[1] R. Chabiniok, P. Moireau, P.-F. Lesault, A. Rahmouni, J.-F. Deux, D. Chapelle. *Estimation of tissue contractility from cardiac cine-MRI using a biomechanical heart model*, in "Biomechanics and Modeling in Mechanobiology", 2012, vol. 11, n° 5, p. 609-630 [*DOI :* 10.1007/s10237-011-0337-8], http://hal.inria.fr/hal-00654541.

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Publications of the year

Doctoral Dissertations and Habilitation Theses

[10] D. TRIMARCHI. *Analysis of downwind sail structures using non-linear shells finite elements – Wrinkle development and fluid interaction effects*, University of Southampton, 2012.

Articles in International Peer-Reviewed Journals

[11] C. BERTOGLIO, P. MOIREAU, J.-F. GERBEAU. *Sequential parameter estimation for fluid-structure problems. Application to hemodynamics*, in "International Journal for Numerical Methods in Biomedical Engineering", April 2012, vol. 28, n^o^ 4, p. 434-455 [*DOI :* 10.1002/CNM.1476], http://hal.inria.fr/inria-00603399.

[12] R. CHABINIOK, P. MOIREAU, P.-F. LESAULT, A. RAHMOUNI, J.-F. DEUX, D. CHAPELLE. *Estimation of tissue contractility from cardiac cine-MRI using a biomechanical heart model*, in "Biomechanics and Modeling in Mechanobiology", 2012, vol. 11, n^o^ 5, p. 609-630 [*DOI :* 10.1007/S10237-011-0337-8], http://hal.inria.fr/hal-00654541.

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Other Publications

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