RESEARCH CENTRE

Inria Centre at Université de Lorraine

IN PARTNERSHIP WITH:

CNRS, Université de Strasbourg

2024

ACTIVITY REPORT

Project-Team

MIMESIS

Computational Anatomy and Simulation for Medicine

IN COLLABORATION WITH: Laboratoire des sciences de l'ingénieur, de l'informatique et de l'imagerie

DOMAIN

Digital Health, Biology and Earth

THEME

Computational Neuroscience and Medicine

Contents

Project-Team MIMESIS

Creation of the Project-Team: 2021 May 01

Keywords

Computer sciences and digital sciences

A2.5. – Software engineering

A3.1.1. – Modeling, representation

A3.1.4. – Uncertain data

A3.2.2. – Knowledge extraction, cleaning

A5.1. – Human-Computer Interaction

A5.3.4. – Registration

A5.4.4. – 3D and spatio-temporal reconstruction

A5.4.5. – Object tracking and motion analysis

A5.6. – Virtual reality, augmented reality

A6.1.1. – Continuous Modeling (PDE, ODE)

A6.1.2. – Stochastic Modeling

A6.1.5. – Multiphysics modeling

A6.2.3. – Probabilistic methods

A6.2.4. – Statistical methods

A6.2.5. – Numerical Linear Algebra

A6.2.8. – Computational geometry and meshes

A6.3.1. – Inverse problems

A6.3.2. – Data assimilation

A6.3.3. – Data processing

A6.3.4. – Model reduction

A9.2. – Machine learning

A9.10. – Hybrid approaches for AI

Other research topics and application domains

B1.2. – Neuroscience and cognitive science

B2.2.6. – Neurodegenerative diseases

B2.4. – Therapies

B2.4.3. – Surgery

B2.6. – Biological and medical imaging

B2.7. – Medical devices

B2.7.1. – Surgical devices

1 Team members, visitors, external collaborators

Research Scientists

- Stéphane Cotin [Team leader, INRIA, Senior Researcher]
- Pablo Alvarez Corrales [INRIA, ISFP, from Oct 2024]
- Hadrien Courtecuisse [CNRS, Researcher]
- Michel Duprez [INRIA, Researcher]
- Axel Hutt [INRIA, Senior Researcher]

Faculty Member

- Vanessa Lleras [UNIV MONTPELLIER, Associate Professor Delegation, from Feb 2024 until Aug 2024]

Post-Doctoral Fellows

- Pablo Alvarez Corrales [INRIA, Post-Doctoral Fellow, until Apr 2024]
- Raphael Bulle [INRIA, Post-Doctoral Fellow, from Oct 2024]

PhD Students

- Sidaty El Hadramy [INRIA]
- Thuc Long Ha [UNIV STRASBOURG, until Nov 2024]
- François Lecomte [INRIA]
- Frédérique Lecourtier [INRIA]
- Negin Majzoubi [INSERM, from Oct 2024]
- Claire Martin [INRIA]
- Josephine Riedinger [INRIA, until Feb 2024]
- Valentina Scarponi [UNIV STRASBOURG]
- Killian Vuillemot [UNIV MONTPELLIER]
- Thomas Wahl [INRIA, until Sep 2024]
- Nicola Zotto [UNIV STRASBOURG]

Technical Staff

- Ishak Barkat [UNIV STRASBOURG, Engineer, from Nov 2024]
- Karl-Philippe Beaudet [INRIA, Engineer, from Mar 2024]
- Skander Bennys [CNRS, Engineer, until Aug 2024]
- Léo Bois [INRIA, Engineer, from Mar 2024 until Sep 2024]
- Robin Enjalbert [INRIA, Engineer]
- Vincent Italiano [INRIA, Engineer, until Nov 2024]
- Antoine Oberle [CNRS, Engineer, until Jun 2024]

Interns and Apprentices

- Andrea Bonifacio [INRIA, Intern, from Apr 2024 until Aug 2024]
- Francesco Dettori [Icube, Intern, from Mar 2024 until Aug 2024]
- Pierre Fonda [UNIV STRASBOURG, Intern, until Jul 2024]
- Victor Michel [UNIV STRASBOURG, Intern, from Feb 2024 until Jul 2024]
- Andrew Zaman [INRIA, Intern, from Jul 2024 until Jul 2024]
- Andrew Zaman [INRIA, Intern, from Apr 2024 until Jun 2024]

Administrative Assistant

- Ouiza Herbi [INRIA]

External Collaborators

- Nazim Haouchine [HARVARD MEDICAL SCHOOL, until Jul 2024]
- Juan Verde [IHU STRASBOURG]

2 Overall objectives

2.1 Team Overview

The MIMESIS team develops numerical methods for computer-based training, surgical planning and computer-assisted interventions. Our aim is to facilitate the development of digital twins and improve their predictive capabilities through novel numerical methods, data assimilation techniques and machine learning. To pursue these directions we have assembled a team with a multidisciplinary background, and have established close collaborations with academic and clinical partners. We contribute to the development of the SOFA framework as a means to disseminate our results to the community.

2.2 Challenges

In a first research axis, our research aims at developing more advanced simulations, with stronger mathematical and biomechanical foundations, and their adaptation to a specific patient. We want, in particular, to develop more stable numerical methods that would, at the same time, be suited for the automatic generation of digital twins of organs. We chose to investigate immersed boundary methods that do not require an exact discretization of the domain. It led to the development of Φ-FEM, a finite element method on domains defined by level-sets that provides better convergence while significantly simplifying the mesh generation process. To achieve real-time computation using complex models based on nonlinear PDEs, we investigate the use of deep learning techniques for accelerating physics-based simulations. Given that our main field of application is computer-guided surgery, we also study the numerical aspects of contact problems. Such problems are very hard to solve in real time, as they involve non-smooth dynamics. In addition, we investigate data assimilation methods to estimate patient-specific model parameters from sparse observations, as they typically occur during surgical interventions. Random processes play an important role in biological systems and need specific mathematical analysis. In neuroscience, stochastic fluctuations have been shown to control oscillatory brain states that may be induced by neurostimulation in clinical practice. To improve our understanding of nonlinear neural dynamics during neurostimulation and thus improve experimental neurostimulation protocols in single patients, we have extended the mathematical analysis of additive noise-induced system evolution.

Our second research axis is derived from our application context and essentially consists of developing optimization and control methods for computer-assisted interventions. At the core of our activity is the hypothesis that data-driven simulation has the potential to bridge the gap between medical data (most often images) and clinical routine by updating pre-operative knowledge with the information available at the time of the procedure. We have been pioneers in the use of biomechanical models and real-time finite element simulation to perform augmented reality on deformable organs. In the field of non-rigid registration, we have demonstrated the benefit of our physics-based approaches as they bring not only an implicit regularization of the solution but also a plausible explanation of the deformation. We have continued this work with an emphasis on robustness to uncertainty and outliers in the information extracted in real-time from image data, and in real-time parameter estimation. The work, initially done using Bayesian methods, has been recently extended through optimal control methods. Optimal control may be achieved in a closed feedback loop and we investigate its implementation in a neurostimulation setup. The objective of this loop is to control the spectral power density of a subject's brain activity. In a Kalman observer feedback model, brain observations are fed into a Kalman Filter which estimates instantaneous stimulation input to the brain in real-time. Another approach treats the brain as a linear time-invariant system and optimizes the brain stimulation input by direct feedback control based on observed brain signals. Finally, in the field of robotic control of flexible structures, we are developing methods for autonomous insertion of needles during percutaneous procedures and autonomous navigation of catheters and guidewires during endovascular interventions. This research combines our expertise in real-time simulation of deformable structures and our results in contact modeling, while the control is either performed via differentiable simulations or using reinforcement learning methods.

3 Research program

3.1 Real-time personalized computational models for interactive applications

3.1.1 Immersed boundary methods

We investigate finite element methods that fall under the class of unfitted (also known as immersed boundary) methods. Because such methods do not require a discretization that strictly conforms to the domain boundary, they are particularly suited for the development of digital twins, as they facilitate the automatic generation of patient-specific simulations on complex geometries. We particularly focus on the development, the numerical analysis and mathematical foundations for a level-set based inverse boundary method that we have called φ-FEM. The main advantage of φ-FEM is that it uses the classical Finite Element tools on unfitted meshes.

3.1.2 Scientific machine learning

Speeding up the simulation of non-linear elastic solids is a field studied by many reasearchers. A variety of solutions has been proposed, including domain decomposition, GPU computing, or dimensionality reduction, to cite just a few. We investigate approaches based on deep neural networks, both in supervised and unsupervised learning scenarios, for which the choice of input/output couples, network architecture and physical laws are critical for accuracy and speed.

This line of work remains has the dual objective of avoiding black box approaches (by keeping the underlying physics law or known numerical schemes in the prediction) and generalizing as much as possible the learned solution to avoid repeated training costs when changing the problem. We currently focus on enabling dynamic simulations, as well as developing deep neural network architectures that provide more genericity in the solution space (by being somewhat invariant to the meshing of the domain for instance).

3.1.3 Non-smooth mechanics

Many clinical interventions rely on mechanical interactions between a device and the anatomy. Surgery and interventional radiology are the two main areas where these interactions are essential and generally complex. In recent years we have continued our activity on constraint modeling and simulation of contacts with friction. The complexity of the problem often leads to unstable numerical approaches, inaccuracy of the solution and slow computation times. This research axis focuses on enhancing computational performance and stability in contact problems using innovative hybrid numerical solvers and asynchronous methods. This is particularly critical for the development of realistic and precise haptics systems for medical tool manipulation, where high-frequency force updates are imposed by fast-changing data.

3.1.4 Endogenous microscopic fluctuations induce macroscopic oscillatory activity

The brain is a complex system with several spatial and temporal scales. The microscopic scales are rather unstructured in space, and activity observations show random fluctuations, whereas upper hierarchical levels at the mesoscopic and macroscopic scales exhibit more regular dynamics. Some years ago, we found in theoretical studies that additive random input on the microscopic scale to random networks tunes the system's stability and may induce stability change. Such so-called bifurcations induce ordered structures, being in space or time or in both. We intend to demonstrate by theoretical work, that evoked synchronization and de-synchronization observed in macroscopic experimental data results from modulation of random fluctuations of underlying microscopic neural activity.

3.2 Optimization and control for computer-aided interventions

3.2.1 Optimal control and differentiable simulation

An important part of our research is dedicated to the development of patient-specific computational models. Although estimating model properties from medical images is not always possible, they highly determine the accuracy of simulations. We address this issue by solving optimization problems where model parameters are derived from intraoperative observations. We investigate mainly two formulations: optimal control and differentiable simulation.

3.2.2 Closed loop control for neuromodulation

Today typical clinical neuromodulation, such as transcranial electric or magnetic stimulation or performance feedback, applies stimulation protocols with pre-defined parameters, such as stimulation intensity, duration and inter-stimulus interval. However, such patient-unspecific open-loop stimulation protocols may not be effective for all patients. We investigate closed-loop neurostimulation protocols for modulating brain activity. These stimulation protocols aim to tune the brain's spectral power distribution in a pre-defined way that has been determined in previous experimental open-loop neurostimulation studies.

3.2.3 Control in medical robotics

Robotics plays an increasingly important role in medical interventions. Yet, current robots have no or very limited autonomy and are essentially teleoperated systems. To bring some level of autonomy in surgical robots, several challenges need to be overcome, in particular the development of control algorithms able to take into account the interaction between deformable instruments and soft tissues. In our work we study two main application fields: needle-based interventions and endovascular procedures.

Many of the proposed solutions address the deformation problem by extracting image features from live medical images and adjusting the pose/motion of the robot locally to compensate for the observed change of state. Such methods are however limited: intraoperative images usually offer poor visibility of anatomical structures and extracting meaningful information in real-time is challenging, making visual servoing strategies non-robust in many real-world situations. In addition, when large deformations occur, the control law of the robot is more challenging to relate with image-based displacements.

In our work, we develop dedicated numerical methods for solving inverse simulations in real-time and derive robotic commands. Our approaches range from numerical optimization of Finite Elements schemes, to deep reinforcement learning methods that map the relationship between the observation space and the control, with a particular focus on the robustness and speed of the control.

4 Application domains

4.1 Patient-specific stent design through shape optimization

Cardiovascular diseases are the world's leading cause of death. Many pathologies can be treated using image-guided catheter procedures such as balloon angioplasty and stenting. However, the risk of post-operative complications and follow-up surgery due to pathological tissue reactions, such as restenosis, is relatively high. This is what motivates computational methods as a tool for improving understanding of the underlying causes and for the computer-aided design of new endovascular devices to prevent postoperative complications in the future. Due in part to their complex geometry and the significant deformations they undergo during insertion, effective simulation of the structure of endoprostheses and their interaction with their environment is necessary and remains a challenge. In this project, we aim at optimizing the stent design to better adapt to the geometry and mechanical characteristics of the artery, and therefore reduce the risk of post-operative complications.

4.2 Computer-based surgical training

Virtual training helps medical students to get familiar with surgical procedures before manipulation of real patients. The development of simulation used for medical training usually requires important computational power, since realistic behaviors are key to deliver a high-fidelity experience to the trainee. Further, the quality of interaction with the simulator (usually via visual and haptic rendering) is also of paramount importance. All these constraints make the development of training systems time-consuming, thus limiting the deployment of virtual simulators in standard medical curriculum.

Our activity in this area is twofold: we continue the development of fast and accurate numerical solutions for computing the interactions between a medical device and anatomical structures, and we investigate means of assessing trainee's performance and ways of providing valuable feedback in the form of a virtual coach.

4.3 Pre-operative planning

Beyond training, clinicians ask for innovative tools that can assist them in the pre-operative planning of an intervention. Using the patient information acquired before the operation, physics-based simulations allow to simulate the effect of therapy with no risk to the patient. The clinicians can thus virtually assess different strategies and select the optimal procedure. Compared to a training simulation, a planning system requires a high accuracy to ensure reliability. Constrained by the time elapsed between the preoperative acquisition and the intervention, the computation must also be efficient.

4.4 Intra-operative guidance

Besides the surgery training and planning, another major need from clinicians is surgical guidance. While the clinician is performing the operation, a guidance system provides enriched visual feedback. This is especially useful with the emergence of minimally invasive surgery (MIS) where the visual information is often strongly limited. It can be used for example to avoid critical areas such as vessels or to highlight the position of a tumor during its resection. In the MIS technique, the clinician does not interact with organs directly as in the open surgery, but manipulates instruments inserted through trocars placed in small incisions in the wall of the abdominal cavity. The surgeon can observe these instruments on a display showing a video stream captured by an endoscopic camera inserted through the navel. The main advantage of the method resides in reducing pain and time recovery, in addition to reducing bleeding and risks of infection. However, from a surgical standpoint, the procedure is quite complex since the field of view is considerably reduced and the direct manipulation of organs is not possible.

4.5 Feedback control of neural activity

In the medical treatment of mental disorders, such as attention deficit disorders or schizophrenia, pharmacological medication plays an important role. However, it is well-known that patients develop resistance to medication after some time and hence an alternative treatment is mandatory. Besides psycho-cognitive treatment, neurostimulation plays a more and more important role. Today typical clinical neurostimulation, such as transcranial electric or magnetic stimulation, applies stimulation protocols with pre-defined parameters, such as stimulation intensity, duration and inter-stimulus interval. However, such patient-unspecific open-loop stimulation protocols may not be effective for all patients. Our research aims to develop a closed-loop neurostimulation protocol.

In one method, we estimated electric stimulation signals based on observed neural activity, such as local field potentials or electroencephalographic data. In this context, we worked together with Philippe Isope at the laboratory INCI in Strasbourg. A different experimental method will provide feedback of a subject's experimental performance during a cognitive experiment. The performance will be visualized on a computer screen while the subject performs a psycho-physical experiment. Moreover, another method applies auditory beat stimulation, which is a sensory neuromodulation technique. We intend to adapt its experimental stimulation parameters (frequency, intensity, stimulation duration) optimally to optimize the individual subject's experimental performance and thus improve her/his cognition.

4.6 Open source software

For many years, members of the team have considered essential to disseminate our research results (and the algorithms to produce them) in an open manner. The objective was to also develop a framework that could be used internally as a means to integrate our various contributions and facilitate validation and technology transfer. Many of our research results have since been released to the community as open source code, either through improvements of SOFA or as plugins of the framework.

SOFA is an efficient and accurate simulation framework written in C++, developed by our team and researchers from a couple of other Inria teams. It is one of the few open source frameworks for the simulation of heterogeneous mechanical systems. It is particularly aimed at real-time applications involving contacts. It is also often aimed at medical applications. Thanks to its high level of modularity, SOFA allows users to rapidly create complex simulations based on the large set of algorithms ranging from collision detection methods to volume rendering to finite element methods. It is structured around an open source core and many plugins, often open source as well. More than 30 researchers, students or engineers have contributed at various degrees to SOFA, for a total of about 1,500,000 lines of code. Today, the project has gone far beyond French borders.

5 Highlights of the year

5.1 Awards

Our work on data-driven endovascular navigation [13] was presented at the Joint AE-CAI | CARE | OR 2.0 workshop at MICCAI 2024, where it won the Outstanding Paper Award.

6 New software, platforms, open data

6.1 New software

6.1.1 SimRender

Name: Simulation Rendering in 3D

Keywords: Modelization and numerical simulations, Data visualization, 3D

Scientific Description: SimRender is a Python package for creating interactive 3D rendering of numerical simulations in a very few lines of code. The main feature is that users can launch an interactive 3D rendering window without blocking the execution of the python process running a numerical simulation. This is very useful for better understanding how optimization processes evolve during deep learning and deep reinforcement learning algorithms and to better detect any errors. The project is compatible with any numerical simulation written in Python and provides dedicated useful features for SOFA numerical simulations.

SimRender provides a simple API for creating and updating 3D objects from simulated data and displaying them with very few lines of code. A viewer can be launched automatically in a python sub-process so as not to block the execution of the main python process. A fast method for sharing 3D data between python sub-processes has been implemented using Shared Nympy Arrays. The viewer is written using Vedo to create various customizable 3D objects (meshes, point clouds, vectors). Using SimRender with any SOFA scene is made even easier by the automatic rendering of several components and the automatic update of data during time steps.

Functional Description: SimRender provides a simple API for creating and updating 3D objects from simulated data and displaying them with very few lines of code. A viewer can be launched automatically in a Python sub-process so as not to block the execution of the main python process. A fast method for sharing 3D data between Python sub-processes has been implemented using Shared Numpy Arrays. The viewer is written using Vedo to create various customizable 3D objects (meshes, point clouds, vectors). Using SimRender with any SOFA scene is made even easier by the automatic rendering of several components and the automatic update of data during time steps.

URL: https://github.com/RobinEnjalbert/SimRender

Contact: Robin Enjalbert

7 New results

7.1 Deformable image registration for tongue morphology prediction from fossil data

Participants: Pablo Alvarez Corrales.

When dealing with the question of the emergence of speech in human evolution, one major requirement is the physical capacity of fossil hominins to articulate the distinctive sounds required for spoken language. Given that the morphology of the vocal tract and the tongue both play a critical role in sound production, biomechanical and acoustic models could be used to directly assess spoken-language production capacity of a given head and neck morphology. However, since fossil remains do not preserve soft tissue, the technical challenge is to be able to predict them, and in particular the tongue, from bony structures alone, so that such assessment is possible. In [1], we propose the use of medical images of the head and neck to register a reference biomechanical tongue model of a living human into a tongue model of any other primate. Since the information from fossil remains is scarce, we propose a hybrid cost function based on paired landmark alignment, intensity information, and smoothness and symmetry regularization to solve the deformable registration problem. We evaluate our method quantitatively on the prediction of a Baboon tongue using validation data from CT scans of the skull and the vocal tract. We further include a mathematical evaluation based on uncertainty quantification methods to evaluate the sensitivity of our predictions to variations of crucial registration parameters. This same methodology has already been applied to Neanderthal fossil data with promising results. The current work focuses on further validation of the proposed methodology and the predictions obtained for the fossil data.

7.2 Digital twins of organs

Participants: Michel Duprez, Vanessa Lleras, Vincent Italiano, Frederique Lecourtier, Stéphane Cotin, Sidaty El Hadramy.

For several years, we have investigated Finite Element methods (FEM) that fall under the class of unfitted (also known as immersed boundary) methods. Because such methods do not require a discretization that strictly conforms to the domain boundary, they are particularly suited for the development of digital twins, as they facilitate the automatic generation of patient-specific simulations on complex geometries. We use a patient-specific biomechanical model to reproduce real-time deformations of an organ by combining Finite Element (FE) simulations and deep neural networks in order to satisfy the very low computational times and accuracy requirements of medical applications [2]. We worked in particular on hyperparameter tuning, implementation improvements, and validation of the method.

Physics-based patient-specific biomechanical models, particularly those using FEM, simulate organ behaviors accurately but are computationally intensive, especially for hyper-elastic tissues. To address this, we introduced U-Mesh, a data-driven approach using a U-Net architecture, achieving real-time inference but reliant on precise stiffness knowledge at training. In [16, 17], we introduced HyperU-Mesh, an extension that integrates a Hypernetwork to condition the U-Mesh based on stiffness prior distributions. By training with FEM-simulated data that varies stiffness under a predefined distribution, HyperU-Mesh ensures accuracy across variable stiffness without retraining. Experimental results highlight its effectiveness across different scenarios, showing comparable accuracy to FEM while significantly improving speed. In [9] we also proposed a method to predict the deformation of a liver model using the centerlines of its vascular system as input of a deep neural network. Information about the vascular network geometry can be obtained, intraoperatively, using ultrasound imaging. The work published in [15] shows how we can differentiate the main branches of this vascular tree.

Moreover, our current results have focused on the development, the numerical analysis and mathematical foundations of a new method called Φ-FEM. The main advantage of our method is that it uses the classical FE tools on unfitted meshes. We have also highlighted that the method significantly improves the convergence when compared to a similar, fitted, discretization of the domain. Recently, we have also shown how to use Φ-FEM simulations to train FNO neural networks (see [23]) and developed a finite-difference scheme inspired by the Φ-FEM paradigm (see [22]). Both approaches significantly reduce computation time. Our current activity on Φ-FEM consists in an Open Source implementation in a SOFA plugin. This is done in relationship with another development activity that integrates automatic differentiation tools from the project FEniCS (www.fenicsproject.org) to quickly and efficiently add new constitutive models in our code base, through simple Python scripting. We are convinced of the impact of this work for both our research activity and the field in general.

7.3 Physics-enhanced synthetic data generation for 2D-3D deformable image registration

Participants: François Lecomte, Pablo Alvarez Corrales, Stéphane Cotin.

In minimally invasive image-guided surgery, several sources of visual information are used. In our context, pre-operative CT-Scan enables the practitioner to segment anatomical structures, while intraoperative fluoroscopic imaging is used for intra-operative navigation. During surgery, deformation of the anatomy leads to a significant mismatch between the fluoroscopic image and the preoperative CT scan. The 2D nature of intra-operative imaging entails a loss of information, making it difficult to reconstruct 3D anatomy from a 2D fluoroscopic image. Moreover, it is practically impossible to generate sufficient quantities of 3D/2D image pairs to directly train a neural network to solve this problem. Synthetic data generation strategies have emerged as a solution, but the existing methods often lack versatility and do not represent well certain types of deformation. Our work in [11] focuses on X-ray to CT 2D-3D deformable image registration for abdominal interventions, where tissue deformation can arise from multiple sources. Unlike previous approaches of data generation relying on statistical models extracted from 4DCT images, our method leverages a single 3D CT image and physically corrected randomized Displacement Vector Fields (DVF) to enable 2D-3D registration for a variety of clinical scenarios. We believe that our approach represents a significant step towards overcoming data scarcity challenges.

7.4 Computer-aided endovascular navigation

Participants: Valentina Scarponi, Michel Duprez, Stéphane Cotin.

Endovascular interventions are the main therapeutic solution adopted to treat endovascular diseases, which are the main cause of death worldwide. Thanks to their minimal invasiveness, they offer many benefits, such as reduced pain and hospital stays, but also present many challenges for clinicians, as they require specialized training and heavy use of X-rays. This is particularly relevant when accessing (i.e., cannulating) small arteries with steep angles, such as most aortic branches. This phase of the procedure can be particularly challenging due to the reduced visual information provided by fluoroscopic images. To address this difficulty, we developed a data-driven endovascular navigation technique that enhances fluoroscopic 2D images in real time by displaying virtual configurations of the catheter and guidewire. In contrast to existing works, proposing either simulators or simple augmented reality frameworks, our approach involves a predictive simulation showing the resulting shape of the catheter after guidewire withdrawal without requiring the clinician to perform this task [19]. Our system demonstrated accurate prediction with a mean 3D error of 2.4±1.3 mm and a mean error of 1.1±0.7 mm on the fluoroscopic image plane between the real catheter shape after guidewire withdrawal and the predicted shape. A user study reported an average intervention time reduction of 56% when adopting our system, resulting in a lower X-ray exposure. This work was presented at the Joint AE-CAI | CARE | OR 2.0 workshop at MICCAI 2024, where it won the Outstanding Paper Award and was the object of two publications [13] [7].

7.5 Physically-inspired regularization for deformable image registration

Participants: Pablo Alvarez Corrales, Stéphane Cotin.

Numerous regularization methods for deformable image registration aim at enforcing smooth transformations, but are difficult to tune in a priori and lack a clear physical basis. To cope with this problem, physically-inspired regularization has been introduced. These methods consider the organs in medical images as hyperelastic bodies, and exploit the theory of continuum mechanics for the design of regularization strategies. In addition to their strong physical basis, they also inherently strengthen desirable properties such as transformation smoothness and invertibility. However, to date, they still require complex domain discretization and resolution schemes. In our work, we have extended these ideas to propose a physically-derived regularization strategy that can be computed at arbitrary points in the domain, therefore not requiring any discretization. Consequently, our strategy is compatible with existing deformable image registration frameworks and optimizers, while maintaining the desirable properties of physically motivated regularization. We have implemented our regularization scheme using deep neural networks [8], and obtained promising results in a 4DCT lung database widely used in the literature for evaluation of deformable image registration methods. We are currently working on exploiting this physically inspired regularization strategy for coping with the problem of information scarcity of 2D-3D deformable image registration.

7.6 Recovering surgically-induced deformations of the liver

Participants: François Lecomte, Juan Verde, Stéphane Cotin.

We have performed an extensive validation on recovering surgically induced deformations of the liver from synthetic X-Ray images [5]. Preliminary experiments on real X-ray images acquired from a porcine model at IHU Strasbourg demonstrated that deformations could be accurately recovered in real X-ray images, achieving an accuracy comparable to that in the synthetic case [18].

7.7 Contact models and haptics

Participants: Claire Martin, Thuc Long Ha, Hadrien Courtecuisse.

Needle-based procedures such as biopsies or radio-frequency ablation (RFA) of tumors are often considered to diagnose and treat liver cancer for their low invasiveness but raise difficulties for practitioners related to needle placement and visibility of internal anatomical structures.

In [10] we proposed an innovative approach for executing robotic needle insertion within deformable living organs. The objective is to maintain the insertion pivot point on the skin, which remains stationary. At the same time, the organs undergo displacement and deformation due to respiration. Therefore, real-time control and precise needle steering are crucial. The proposed method relies on isolated objective constraints to ensure the objectives while steering the needle along a predefined trajectory. The needle insertion process benefits from FE models to simulate the environment and address the inverse problem to drive the robot's end effector (EE) by re-evaluating the objective functions in the constraint space for each time step. As a result, the desired motion of the robot's EE can be computed at a small cost for non-linear functions in real time, resulting in better precision and reducing stress caused to the organs.

In [14] we developed a contact model specific to needle-tissue interactions to improve the realism of the resulting haptic rendering. We present a novel method to update the compliant coupling at high rates of a complete contact system involving the mechanics of a large object and the complete model of a flexible needle. These updates allow to adapt the contact directions to the needle deformations in the haptic thread, with the aim of improving the resulting haptic feedback. Updates of contact directions and the related mechanical system according to high-rate deformations decrease force feedback artifacts associated with low-rate mechanics while maintaining high-rate performances for the haptic loop.

7.8 Order in random systems

Participants: Axel Hutt.

The brain is a complex system with several spatial and temporal scales. The microscopic scales are rather unstructured in space, and activity observations show random fluctuations, whereas upper hierarchical levels at the mesoscopic and macroscopic scales exhibit more regular dynamics, see e.g. [25]. In previous studies, we found that additive random input on the microscopic scale to random networks tunes the system's stability and may induce stability changes. Such so-called bifurcations induce ordered structures, being in space or time or in both. This additive noise-induced system evolution (ANISE) has been shown to describe successfully synchronization and desynchronization observed in electroencephalographic data.

We have extended recent corresponding studies by considering delayed interactions along myelinated axonal fibers in the brain [24]. These fibers connect single neurons and the propagation time of traveling pulses along these fibers represents the interaction delay of neurons. The transmission delay in random stochastic networks affects the system's stationary state and tunes its linear response to external stimulation.

7.9 Influence of neural network heterogeneity on neurostimulation impact

Participants: Axel Hutt.

Brain stimulation is a modern therapy in clinical practice. The various types of stimulation affect the brain's internal structure and functioning, which results to learning processes and, in case of mental disorders, to improving the patient's health condition. To better understand the conditions under which neurostimulation may modulate the brain dynamics, we have studied the impact of heterogeneity in neural systems on the stimulation. In fact, more heterogenous neural systems render the system more resilient to external stimulation [4]. Since neural network heterogeneity may develop over time (on a time scale of days or weeks) and may be different in each brain area, this neural system diversity affects the impact of neurostimulation.

7.10 Classification of gait motion in clinical patients

Participants: Axel Hutt.

Gait analysis plays a significant role in clinical assessments to discriminate neurological disorders from healthy controls, to grade disease severity, and to further differentiate dementia subtypes. In this work [20], we apply recurrence structure analysis (RSA) as a method to classify pathological gait tasks from 3D skeleton pose sequences. For each dataset, RSA yields symbolic sequences, whose complexity reflects the subject's gait movement complexity. A new gait movement model permitted to derive novel complexity measures, which serve as classification features. Applying a Multi-Layer Perceptron classification to healthy and pathological subjects suffering from Alzheimer Disease (AD) or Dementia with Lewy Bodies (DLB) permits to distinguish subjects with regular and irregular gait and AD and DLB patients. Moreover, the performed analysis indicates that arms movement is more informative in the distinction of AD and DLB than legs movement. A final comparison to previous studies of similar data demonstrates that the proposed model-based feature classification outperforms some previous data-based feature classification methods.

7.11 Optimal control to limit epidemia

Participants: Michel Duprez.

There exists no efficient vaccine against arboviruses like Malaria, Dengue, Lymphatic Filariasis, Zika, Chikungunya, Yellow fever, and Japanese encephalitis. One way to limit the propagation of such diseases is to fight their vector which is the mosquito. The sterile insect technique (SIT) is a biological control technique that can be used either to eliminate or decay a wild mosquito population under a given threshold to reduce the nuisance or the epidemiological risk. We have studied the mathematical properties of the optimal release strategies in order to maximize the efficiency of this technique. In [21, 3], we have studied the impact of the migration on the control strategy.

7.12 Neural controllers for autonomous medical robots

Participants: Stéphane Cotin, François Lecomte, Valentina Scarponi, Michel Duprez.

The primary therapeutic solution for cardiovascular diseases is endovascular interventions, thanks to their minimal invasiveness and low costs. However, these procedures are limited by their complexity and by the need of acquiring fluoroscopic images to visualize the internal structures of the patients. The acquisition of these images requires using X-rays, which are dangerous for the health of both the patient and the clinician. Furthermore, to visualize the vessel structures, it is necessary to inject a contrast agent, which is harmful for the patient's kidneys. To address these limitations, the only partial solution that exists today is the use of endovascular robots, which allow the caregiver to perform the intervention far away from the operative field. However, these robots are only master-follower devices, which are not able to provide additional support to the clinician. To address this limitation, we proposed a zero-shot learning strategy for three-dimensional autonomous endovascular navigation. Using a very small training set of branching patterns, our reinforcement learning algorithm is able to learn a control that can then be applied to unseen vascular anatomies without retraining, even when the anatomy is moving. To retrieve the movement of the anatomy, starting from fluoroscopic images, we proposed a method to estimate the motion of the anatomy from single view fluoroscopy images. This allows to obtain a system able to automatically navigate across a moving vascular anatomy under fluoroscopic imaging, even without injecting a contrast agent. We validated our method in a simulated environment on various synthetic static anatomies on two realistic scenarios: a simulated beating heart and a liver subjected to breathing motion. Our approach leads to an average success rate of 95% in reaching random targets within these anatomies. This work was presented at two international conferences: International Conference on Intelligent Robots and Systems (IROS 2024) and International Conference on Information Processing in Computer-Assisted Interventions (IPCAI 2024). It led to the publication of 2 scientific articles [12] and [6].

8 Bilateral contracts and grants with industry

8.1 Bilateral contracts with industry

Participants: Stéphane Cotin, Michel Duprez, François Lecomte, Valentina Scarponi.

In November 2024, we have started a 2-year collaboration with the company LN Robotics based in South Korea. We will work on fluoroscopic image processing and autonomous robotic control.

9 Partnerships and cooperations

Participants: Axel Hutt.

9.1 International research visitors

9.1.1 Visits of international scientists

Camille Gontier

Status Post-Doc

Institution of origin: University of Pittsburg

Country: USA

Dates: March

Context of the visit: research visit

Mobility program/type of mobility: research stay

9.1.2 Visits to international teams

Axel Hutt

Visited institution: Bernstein Center Freiburg

Country: Germany

Dates: April

Context of the visit: Research visit and seminar talk

Mobility program/type of mobility: research stay

Axel Hutt

Visited institution: Clinic for Psychiatry, University Hospital Freiburg

Country: Germany

Dates: July

Context of the visit: Research visit and seminar talk

Mobility program/type of mobility: research stay

Axel Hutt

Visited institution: Department of Mathematics, University of Dundee

Country: United Kingdom

Dates: October

Context of the visit: Research visit and seminar talk

Mobility program/type of mobility: research stay

9.2 National initiatives

ADT – AI for Surgical Vision

Title: AI for Surgical Vision

Duration: 2021 – 2024

Coordinator: Stéphane Cotin

Partners:

- BOPA innovation chair
- Paul Brousse Hospital

Inria contact: stephane.cotin@inria.fr

Summary: The objective of the project is to develop and integrate computer vision algorithms capable of processing images from the operating room in real time into a clinically usable augmented reality prototype. This project reinforces the work carried out in partnership with the "Augmented Operating Room" (BOPA) innovation chair at Paul Brousse Hospital in Paris. The project is part of the Blok-Viz axis whose goal is to process video feeds of the operating field to extract relevant information on which AI algorithms dedicated to attention analysis, registration and augmented reality can be based.

ANR – SPECULAR

Title: Simulation of needle insertion with virtual reality and haptics.

Duration: 2021 – 2025

Coordinator: Stephane Cotin (MIMESIS)

Partners:

- Inria Antenna in Strasbourg, MIMESIS team (France)
- Inria Research Center at Université de Lille, DEFROST team (France)
- InfinityTech 3D (France)

Inria contact: stephane.cotin@inria.fr

Summary: The objective of this project is to develop a complete virtual reality training system for radiofrequency ablation. The research program includes the real-time simulation of the needle-organ interactions, realistic and immersive rendering of the operating room, medical image generation and haptic feedback.The results of this project will accelerate the training of these procedures and could change the standard of care which remains a surgery in many cases.

ANR – VATSOP

Title: Images and models for computer guidance during Video Assisted Thoracic Surgery (VATS).

Duration: 2021 – 2025

Coordinator: Jean-Louis Dillenseger (LTIS Rennes)

Partners:

- TIMC-IMAG Laboratory, Grenoble (France)
- Inria Antenna in Strasbourg, MIMESIS team (France)
- LTSI Laboratoire Traitement du Signal et de l'Image (Rennes, France)

Inria contact: stephane.cotin@inria.fr

Summary: In minimally invasive image-guided surgery, several sources of visual information are used. In our context, pre-operative CT scans enable the practitioner to segment anatomical structures, while intra-operative fluoroscopic imaging is used for intra-operative navigation. The 2D nature of intra-operative imaging implies a loss of information, making it difficult to reconstruct 3D anatomy from a single 2D fluoroscopic image. However, the pre-operative 3D anatomy is known from the pre-operative CT scan. To augment intra-operative fluoroscopic imaging with accurate 3D anatomical information, it is necessary to recover surgery-related deformations, an operation known as non-rigid registration. Our work aims to develop a non-rigid registration method to correct the mismatch between 3D pre-operative imaging and 2D intra-operative imaging. Our approach uses a fully convolutional network architecture to solve the associated inverse problem. Because there exists no dataset of 3D/2D image pairs suited to train a neural network to solve this problem, a synthetic data generation method is developed to generate a training dataset. Supervised learning is performed on this synthetic training data, with Digitally Reconstructed Radiographs as input and displacement fields as output. Contrary to other 2D-3D registration methods, this novel data generation approach does not rely on a statistical motion model. This enables the network to accurately predict deformations beyond predetermined motion patterns. As an example of clinical application, we show that our model can accurately handle surgery-induced deformations in the liver.

ANR – TRECOS

Title: New Trends in Control and Stabilization: Constraints and Non-local Terms.

Duration: 2020 – 2024

Coordinator: Sylvain Ervedoza (Institut de Mathématiques de Bordeaux, Laboratoire Traitement du Signal et de l'Image)

Partners:

- IMT Institut de Mathématiques de Toulouse (France)
- Inria Antenna in Strasbourg, MIMESIS team (France)
- IMB Institut de mathématiques de Bordeaux (France)
- LJLL Laboratoire Jacques-Louis Lions, Paris (France)

Inria contact: michel.duprez@inria.fr

Summary: The goal of this project is to develop new solutions in control theory for partial differential equations, motivated by models arising in ecology and biology. The project focuses on two aspects. The first one is related to the constraints required on the controls or on the controlled trajectories, for instance positivity constraints, which appear naturally when the state models a temperature. The second aspect concerns the questions of controllability and stabilization of problems involving non-local operators, such as integral operators in space, in order to take into account phenomena depending on the total mass of the population for instance, or delay and memory terms, such as in visco-elastic fluids, often used to a model blood flows, or more generally models described by systems coupling hyperbolic and parabolic effects.

ANR – S-KELOID

Title: Understanding Keloid Disorders: A multi-scale in vitro/in vivo/in silico approach towards digital twins of skin organoids on the chip.

Duration: 2021 – 2025

Coordinator: Raluca Eftimie and Stéphane Bordas (Univ. Luxembourg)

Partners:

- Laboratoire de Mathématiques de Besançon (France)
- CHU de Besançon (France)
- FEMTO-ST, Besançon (France)
- Institut Mathématiques de Bourgogne, Dijon (France)
- Université du Luxembourg (Luxembourg)
- Inria Antenna in Strasbourg, MIMESIS team (France)

Inria contact: michel.duprez@inria.fr

Summary: Mathematical and numerical modeling approaches allow us to integrate pathological processes that occur across different scales: single cell, cell assembly and tissue. The S-Keloid project aims to investigate the role of mechanical and inflammatory environmental factors on cells associated with keloid disorders, which are the formation of pathological scars. From applying experimental tests at tissue-scale and using a multiscale approach, the mechanical stress fields will be integrated into the 3D mathematical model. Parameter identification, optimization and their use across multiple scales will ensure the realism of the models and the quantitative and qualitative predictions of the keloid disorder.

ANR – PhiFEM

Title: Φ-FEM : development of a Finite Element Method for the design of real-time digital twins in surgery

Duration: 2022 – 2026

Coordinator: Michel Duprez (Inria)

Partners:

- MIMESIS team
- Laboratoire de Mathématiques de Besançon (France)
- Institut de Mathématiques Alexander Grothendieck, Montpellier (France)
- Institut de Recherche en Mathématiques Appliquées, Strasbourg (France)

- Université du Luxembourg (Luxembourg)

Inria contact: michel.duprez@inria.fr

Summary: Φ-FEM is a recently proposed finite element method for the efficient numerical solution of partial differential equations posed in domains of complex shapes, using simple regular meshes. The main goal of this project is to further develop ϕ-FEM, turning it into a tool for efficient, patient-specific and real-time simulations of human organs. To reach this objective, we shall adapt ϕ-FEM to the equations appropriate to biomechanics, provide an efficient implementation for it allowing for the use of actual organ geometries, and finally combine it with convolutional neural networks to make it real time after training. The ultimate, long-term, goal is thus to contribute to the construction of digital twins of organs able to guide the surgical act in real time using information acquired before the operation and to reduce the costs of a medical doctors' training by working on visual organs. The innovation of ϕ-FEM lies in its ability to combine the ease of implementation of classical immersed boundary methods with the accuracy of more recent CutFEM/XFEM approaches. It incorporates, by its very construction, the popular description of geometry by Level Set functions, which can represent the real geometry with whatever accuracy desired which makes this approach numerically less expensive than classical finite element methods. The ϕ-FEM paradigm will also be used to develop efficient registration algorithms. Our results will be integrated into the open-source SOFA platform developed in the MIMESIS team to facilitate dissemination.

National Exploratory Action – A/D Drugs

Title: A/D Drugs

Duration: 2020 – 2024

Coordinator: Axel Hutt

Partners: Didier Pinault (INSERM 1114)

Participants: Axel Hutt, Joséphine Riedinger, Didier Pinault

Summary: When it comes to treating mental disorders, the emergence of resistance to medication is a major problem. Replacing chemical medicine with digital medicine (neural stimulation) could be one way of getting around the problem. We will deploy a process of data assimilation and control in order to adapt stimulation to each patient. But this research is not without its risks — very little is known about the links between the effect of the chemical molecules and neurostimulation (www.inria.fr/en/ad-drugs-exploratory-action-aimed-optimising-neurostimulation).

9.2.1 National Collaborations

At the national level, the MIMESIS team collaborates with:

- **Team *Psychiatrie* at INSERM 1329** in Strasbourg. In this collaboration with Anne Bonnefond and Anne Giersch, Axel Hutt and his collaboration partners attempt to relate behavioral and electrophysiological observation data in humans to the subjects' state of attention and perception of time. These objectives are part of two corresponding co-supervised PhD-projects.

- **Institute Neurosciences Cellulaires Et Intégratives (INCI)** in Strasbourg. Axel Hutt and Philippe Isope (INCI) attempt to implement a closed-loop feedback control loop in INCI's animal laboratory to control the time perception of mammals. These animals serve as animal models for human patients suffering from schizophrenia.

10 Dissemination

10.1 Promoting scientific activities

10.1.1 Scientific events: organization

Member of the organizing committees

- Axel Hutt was member of the organizing committee of the Summer School *Advanced tools for data analysis in neuroscience* in Strasbourg (September 2024)
- Hadrien Courtecuisse organized the Survihumo workshop at the RO-Man conference.
- Hadrien Courtecuisse served as local organizing committee chair for the CASA 2025 conference.

10.1.2 Scientific events: selection

Chair of conference program committees

- Axel Hutt was Co-Chair of the Programme Committee of the *Computational Neuroscience Organization (OCNS)*, 2023-2024.

Reviewer

- Axel Hutt was reviewer for oral and poster contributions at the *Computational Neuroscience Organization (OCNS)*
- Pablo Alvarez Corrales was reviewer for the 27th International Conference on Medical Image Computing and Computer Assisted Intervention (MICCAI 2024).

10.1.3 Journal

Member of the editorial boards

- Axel Hutt is Associate Editor of the *Journal of Clinical Medicine*
- Axel Hutt is Chief Section Editor of *Frontiers in Applied Mathematics and Statistics - Dynamical Systems*
- Stéphane Cotin is Associate Editor of the *Medical Image Analysis* journal

Reviewer - reviewing activities

- Axel Hutt was reviewer for the journals *PLoS Computational Biology, Medicine, Mind and Matter, Physica D, SIAM Journal on Applied Mathematics, Brain Sciences, Cells, Qeios, Behavioral Sciences* and *Sensors.*
- Pablo Alvarez Corrales was reviewer for *IEEE Transactions on Medical Imaging.*

10.1.4 Invited talks

- Michel Duprez gave a talk in the workshop BIO-CIVIP (November 2024, Fréjus)
- Michel Duprez gave a talk in the conference ECCOMAS (June 2024, Lisbon)
- Michel Duprez gave a talk in the workshop "Jounée Numérique de Besançon" (January 2024, Besançon)
- Michel Duprez gave a talk in the conference WONAPDE (January 2024, Concepcion, Chili)
- Michel Duprez gave a talk in the seminar MOCO, IRMA, (September 2024, Strasbourg)

- Michel Duprez gave a talk in the seminar MLMS, Icube, (September 2024, Strasbourg)
- Michel Duprez gave a talk in the seminar MACARON, IRMA (February 2024, Belmont, France)
- Axel Hutt gave a talk in the workshop *Neural Diversity and Computation - Towards a Mathematical Account of Tissue Heterogeneity in the Brain* on the Bernstein Conference (May 2024,Frankfurt / Main, Germany)
- Axel Hutt gave a talk in the workshop *Besançon Numerical Days: Data Driven Computing and Modelling in Biology* (January 2024, Besançon, France)
- Axel Hutt gave a talk in the workshop *Data Science and AI* at iCube (April 2024, Strasbourg, France)
- Axel Hutt gave a seminar talk at ITI IRMIA++ (January 2024, Strasbourg, France)
- Axel Hutt gave a seminar talk in the Inria-team PASTA (May 2024, Nancy, France)
- Axel Hutt gave a seminar talk at Mathematical Department of University of Dundee (October 2024, Dundee, Scotland)
- Axel Hutt gave an online-talk in the Neuroscience-seminar at University of Nottingham (March 2024, University of Nottingham, England)
- Axel Hutt gave a talk at the *Summer School | Advanced tools for data analysis in Neuroscience* (September 2024, Strasbourg, France)
- Axel Hutt gave a seminar talk at the Bernstein Center Freiburg (April 2024, Freiburg, Germany)
- Axel Hutt gave a talk at the workshop *The numerical brain* (September 2024, Amsterdam, Netherlands)
- Pablo Alvarez Corrales was invited to the closure event of the *Computer Assisted Medical Interventions (CAMI) LABEX* project (November 2024, Grenoble)

10.1.5 Leadership within the scientific community

- Stéphane Cotin is scientific manager for the MediTwin project (2024-2029) involving 9 Inria teams
- Stéphane Cotin is the main scientific lead for the PREMYOM project (2024-2029) involving 3 Inria teams

10.1.6 Scientific expertise

- Hadrien Courtecuisse was reviewer for the National Research Agency *ANR*.
- Axel Hutt was reviewer for the National Research Agency *ANR*.
- Axel Hutt was invited as expert on *Digital Addiction* at the *European Consumer Summit* organized by the *European Commission* (April 2024)
- Axel Hutt was reviewer of the PhD thesis of Houssem Meghnoudj, Université Grenoble-Alpes.
- Stéphane Cotin was examiner and president of the PhD committee for Thomas Saigre, Mathematical Faculty, Strasbourg University.
- Stéphane Cotin was reviewer of the PhD thesis of Vladimir Poliakov, University of Leuven.

10.1.7 Research administration

Hadrien Courtecuisse was elected member of the iCube laboratory council (Strasbourg) for 2023/2024

10.2 Teaching - Supervision - Juries

10.2.1 Teaching

- License:
  - Sidaty El Hadramy, *MPA Algebra and Analysis*, 20h, L1 and L2, University of Strasbourg
- Master:
  - Valentina Scarponi, *MECANOBIOLOGIE - Matériaux pour la Santé*, 4h, M1 Faculté de Chirurgie Dentaire, University of Strasbourg
  - Michel Duprez, *Optimal control*, 28h, M2, University of Strasbourg.
  - Michel Duprez, *Incertitude quantification*, 14h, M2, University of Strasbourg.
  - Michel Duprez, *Calcul Scientifique*, 10h, M2, University of Strasbourg
  - Hadrien Courtecuisse, *Real-time simulation*, 80h, M2, University of Strasbourg
  - Michel Duprez, *Optimisation*, 28h, M1, University of Strasbourg
- Lecture:
  - Axel Hutt, *Evoked brain activity*, 2h, *Master of Neuroscience*, University of Strasbourg
  - Stéphane Cotin, *Numerical simulation and machine learning*, ITI HealthTech Strasbourg, May
  - Stéphane Cotin, *Medical imaging, simulation, and AI*, ITI IRMIA Strasbourg, November

10.2.2 Supervision

- Master 1:
  - Axel Hutt supervised Ismail Unlu. Title: *Les canaux ioniques de* Ca^{2+} *aux synapses dans le contexte de plasticité et d'apprentisage*
  - Axel Hutt supervised Vincent Kress. Title: *L'échange des informations entre les neurones.*
  - Axel Hutt supervised Charlotte Kruzic. Title: *Stimulation auditive par des tons isochrones et son effect sur l'attention des humains.*
  - Axel Hutt supervised Sabina Askerova. Title: *Analyse spectral de données neuronales.*
- Master 2:
  - Axel Hutt (together with Hyewon Seo (MLMS)) supervised Gauthier Debes. Title: *C-HUMBLE: Classification of human body movement with application to Lewy Body Disease*
  - Stéphane Cotin supervised Andrea Bonifacio (Politecnico Milano, Italy). Title: *Learning and predicting the physics of dynamical elastic objects*
- PhD projects:
  - Axel Hutt supervised Joséphine Riedinger (2020-2024). Title: *Closed-loop transcranial electric stimulation of neural networks in a rat psychosis model*
  - Axel Hutt is supervising Negin Majzoubi together with Anne Bonnefond (INSERM 1329) (2024-2027). Title: *Effets neurophysiologiques et comportementaux du feedback de performance: un nouvel outil numérique pour améliorer le traitement des symptômes attentionnels dans le TDAH*
  - Axel Hutt supervised Thomas Wahl together with Michel Duprez (2021-2024). Title: *Model-based closed-loop neurostimulation with application to schizophrenia*
  - Hadrien Courtecuisse supervised Ziqiu Zeng (2019-2024). Title: *Real-Time FE Simulation for Large-Scale Problems Using Precondition-Based Contact Resolution and Isolated DOFs Constraints*

- Michel Duprez supervises Killian Vuillemot (October 2022-September 2025) together with Vanessa Lleras and Mohammadi Bijan. Title: *Unfitted finite element method for the development of organ digital twins*
- Michel Duprez supervised Valentina Scarponi (2021-2024) together with Florent Nageotte and Stéphane Cotin. Title: *Autonomous Catheter Navigation*
- Stéphane Cotin supervises Nicola Zotto (2021-2025) Title: *Combining AI and biomechanics for computer-assisted interventions*
- Stéphane Cotin supervised Sidaty El Hadramy (2021-2024) Title: *AI-enabled IVUS-guided augmented reality for liver surgery*
- Stéphane Cotin supervised François Lecomte (2021-2024) Title: *Enhancing Fluoroscopy-Guided Procedures with Neural Network-Based Deformable Organ Registration*
- Michel Duprez supervises Frédérique Lecourtier (2023-2026) together with Emmanuel Franck and Vanessa Lleras. Title: *Finite element methods and neural networks for augmented surgery*

10.2.3 Juries

- Stéphane Cotin and Michel Duprez were members of the PhD committee (and supervisor) of the thesis of Valentina Scarponi, Strasbourg University, December
- Stéphane Cotin was member of the PhD committee (and supervisor) of the thesis of François Lecomte, Strasbourg University
- Stéphane Cotin and Michel Duprez were members of the PhD committee (and supervisor) of the thesis of Sidaty El Hadramy, Strasbourg University
- Axel Hutt and Michel Duprez were members of the PhD committee (and supervisor) of the thesis of Thomas Wahl, Strasbourg University, December
- Axel Hutt was member of the PhD committee as reviewer of Houssem Meghnoudj, Université Grenoble-Alpes, January 2024.

11 Scientific production

11.1 Publications of the year

International journals

[1] P. Alvarez, M. El Mouss, M. Calka, A. Belme, G. Berillon, P. Brige, Y. Payan, P. Perrier and A. Vialet. 'Predicting primate tongue morphology based on geometrical skull matching. A first step towards an application on fossil hominins'. In: *PLoS Computational Biology* 20.1 (22nd Jan. 2024), e1011808. DOI: 10.1371/journal.pcbi.1011808. URL: https://hal.science/hal-04448078 (cit. on p. 8).

[2] S. Cotin, G. Mestdagh and Y. Privat. 'Organ registration from partial surface data in augmented surgery from an optimal control perspective'. In: *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* 480 (10th Jan. 2024), p. 20230197. DOI: 10.1098/rspa.2023.0197. URL: https://hal.science/hal-04043695 (cit. on p. 9).

[3] Y. Dumont and M. Duprez. 'Modeling the impact of rainfall and temperature on sterile insect control strategies in a Tropical environment'. In: *Journal of Biological Systems* 32.1 (5th Jan. 2024), pp. 311–347. DOI: 10.1142/S0218339024500128. URL: https://hal.science/hal-03811327 (cit. on p. 12).

[4] A. Hutt, D. Trotter, A. Pariz, T. A. Valiante and J. Lefebvre. 'Diversity-induced trivialization and resilience of neural dynamics'. In: *Chaos: An Interdisciplinary Journal of Nonlinear Science* (2024). URL: https://inria.hal.science/hal-04162586. In press (cit. on p. 12).

[5] F. Lecomte, J.-L. Dillenseger and S. Cotin. 'CNN-based real-time 2D-3D deformable registration from a single X-ray projection'. In: *Journal of Clinical Medicine* 11.7 (1st Mar. 2024), p. 1845. DOI: 10.48550/arXiv.2212.07692. URL: https://inria.hal.science/hal-04387845 (cit. on p. 10).

[6] V. Scarponi, M. Duprez, F. Nageotte and S. Cotin. 'A Zero-Shot Reinforcement Learning Strategy for Autonomous Guidewire Navigation'. In: *International Journal of Computer Assisted Radiology and Surgery* 19 (16th Apr. 2024), pp. 1185–1192. DOI: 10.1007/s11548-024-03092-4. URL: https://inria.hal.science/hal-04488626 (cit. on p. 13).

[7] V. Scarponi, J. Verde, N. Haouchine, M. Duprez, F. Nageotte and S. Cotin. 'FBG-Driven simulation for virtual augmentation of fluoroscopic images during endovascular interventions'. In: *Healthcare Technology Letters* (7th Dec. 2024). DOI: 10.1049/htl2.12108. URL: https://inria.hal.science/hal-04834683 (cit. on p. 10).

International peer-reviewed conferences

[8] P. Alvarez and S. Cotin. 'Deformable Image Registration with Stochastically Regularized Biomechanical Equilibrium'. In: *2024 IEEE 21th International Symposium on Biomedical Imaging (ISBI)*. IEEE 21th International Symposium on Biomedical Imaging. Athens, Greece: IEEE, 27th Apr. 2024, pp. 1–5. DOI: 10.1109/ISBI56570.2024.10635231. URL: https://hal.science/hal-04356505 (cit. on p. 10).

[9] S. El Hadramy, J. Verde, N. Padoy and S. Cotin. 'Towards real-time vessel guided augmented reality for liver surgery'. In: IEEE International Symposium on Biomedical Imaging (ISBI 2024). Athenes, Grece, Greece, 2024. URL: https://inria.hal.science/hal-04387242 (cit. on p. 9).

[10] T. L. Ha, J. Bert and H. Courtecuisse. 'Real-time Robotic Flexible Needle Insertion In Deformable Living Organs Using Isolated Objective Constraint'. In: IEEE RSJ International Conference on Intelligent Robots and Systems - IROS 2024. Abu Dabi, United Arab Emirates, 14th Oct. 2024. URL: https://inria.hal.science/hal-04681176 (cit. on p. 11).

[11] F. Lecomte, P. Alvarez, S. Cotin and J.-L. Dillenseger. 'Beyond respiratory models: a physics-enhanced synthetic data generation method for 2D-3D deformable registration'. In: *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR) Workshops*. Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR) Workshops. Seattle (USA), Washington, United States, June 2024, pp. 2413–2421. URL: https://hal.science/hal-04599413 (cit. on p. 9).

[12] V. Scarponi, F. Lecomte, M. Duprez, F. Nageotte and S. Cotin. 'Autonomous Guidewire Navigation in Dynamic Environments'. In: International Conference on Intelligent Robots and Systems. Abu Dhabi, United Arab Emirates, 14th Oct. 2024. URL: https://inria.hal.science/hal-04681908 (cit. on p. 13).

[13] V. Scarponi, J. Verde, N. Haouchine, M. Duprez, F. Nageotte and S. Cotin. 'FBG-Driven simulation for virtual augmentation of fluoroscopic images during endovascular interventions'. In: Medical Imaging and Augmented Reality, Augmented Environments for Computer Assisted Interventions (AE-CAI), Computer Assisted and Robotic Endoscopy (CARE) and Context-Aware Operating Theaters (OR 2.0) - MICCAI 2024 workshop. Marrackech, Morocco, 6th Oct. 2024. URL: https://inria.hal.science/hal-04834732 (cit. on pp. 7, 10).

Conferences without proceedings

[14] C. Martin, C. Duriez and H. Courtecuisse. 'High Rate Mechanical Coupling of Interacting Objects in the Context of Needle Insertion Simulation With Haptic Feedback'. In: International Conference on Intelligent Robots and Systems (IROS 2024). Abu Dhabi, United Arab Emirates, 14th Oct. 2024. URL: https://hal.science/hal-04750673 (cit. on p. 11).

Edition (books, proceedings, special issue of a journal)

[15] *Towards Real-time Intrahepatic Vessel Identification in Intraoperative Ultrasound-Guided Liver Surgery*. MICCAI 2024. 1st Oct. 2024. URL: https://hal.science/hal-04710612 (cit. on p. 9).

[16] *HyperU-Mesh: Real-time deformation of soft-tissues across variable patient-specific parameters*. Computational Biomechanics Workshop at MICCAI 2024. 1st Jan. 2024. URL: https://hal.science/hal-04651137 (cit. on p. 9).

Doctoral dissertations and habilitation theses

[17] S. El Hadramy. 'AI-enabled IVUS-guided augmented reality for liver surgery'. University of Strasbourg, 2nd Dec. 2024. URL: https://hal.science/tel-04834247 (cit. on p. 9).

[18] F. Lecomte. 'Enhancing Fluoroscopy-Guided Procedures with Neural Network-Based Deformable Organ Registration'. Université de Strasbourg; Inria, 18th Dec. 2024. URL: https://hal.science/tel-04875966 (cit. on p. 10).

[19] V. Scarponi. 'Towards Autonomous Endovascular Surgery: Development of Assistance Tools for Computer-Aided Interventions'. Strasbourg University, 9th Dec. 2024. URL: https://inria.hal.science/tel-04837214 (cit. on p. 10).

Reports & preprints

[20] G. Debes, D. Wang, P. beim Graben, F. Blanc, C. Muller, H. Seo and A. Hutt. *Gait Motion Classification for Neurodegenerative Diseases by Recurrence Structure Analysis*. 20th Sept. 2024. URL: https://inria.hal.science/hal-04707101 (cit. on p. 12).

[21] Y. Dumont, M. Duprez and Y. Privat. *Sterile Insect Technique in a Patch System: Influence of Migration Rates on Optimal Single-Patch Releases Strategies*. 10th Sept. 2024. URL: https://hal.science/hal-04693417 (cit. on p. 12).

[22] M. Duprez, V. Lleras, A. Lozinski, V. Vigon and K. Vuillemot. *Phi-FD : A well-conditioned finite difference method inspired by phi-FEM for general geometries on elliptic PDEs*. 10th Oct. 2024. URL: https://hal.science/hal-04731164 (cit. on p. 9).

[23] M. Duprez, V. Lleras, A. Lozinski, V. Vigon and K. Vuillemot. *Phi-FEM-FNO: a new approach to train a Neural Operator as a fast PDE solver for variable geometries*. 22nd Feb. 2024. URL: https://hal.science/hal-04473794 (cit. on p. 9).

[24] J. Lefebvre, A. Clappison, L. André and A. Hutt. *Myelin-induced gain control in nonlinear neural networks*. 13th Dec. 2024. URL: https://inria.hal.science/hal-04835140 (cit. on p. 11).

Scientific popularization

[25] A. Hutt. 'On "Synergetics" by Hermann Haken (1976)'. In: *Foundational Papers in Complexity Science*. 1st May 2024. URL: https://inria.hal.science/hal-04461802 (cit. on p. 11).