Activity Report 2019

Team MIMESIS

Computational Anatomy and Simulation for Medicine

Inria teams are typically groups of researchers working on the definition of a common project, and objectives, with the goal to arrive at the creation of a project-team. Such project-teams may include other partners (universities or research institutions).

RESEARCH CENTER
Nancy - Grand Est

THEME
Computational Neuroscience and Medicine

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Team MIMESIS

Creation of the Team: 2015 July 01

Keywords:

Computer Science and Digital Science:

- 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
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- A6.1.1. - Continuous Modeling (PDE, ODE)
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- A9.2. - Machine learning
- A9.10. - Hybrid approaches for AI

Other Research Topics and Application Domains:

- B2.4. - Therapies
- B2.4.3. - Surgery
- B2.6. - Biological and medical imaging
- B2.7. - Medical devices
- B2.7.1. - Surgical devices

1. Team, Visitors, External Collaborators

Research Scientists

Stéphane Cotin [Team leader, Inria, Senior Researcher, HDR]
Hadrien Courtecuisse [CNRS, Researcher]
Axel Hutt [Inria, Senior Researcher, from Nov 2019, HDR]
Igor Peterlik [Inria, Researcher, until Jul 2019]

Post-Doctoral Fellows

Nava Schulmann [Politecnico di Milano, PostDoc, from November 2019]
Mohamed Ryadh Haferssas [Inria, Post-Doctoral Fellow]
Antoine Petit [Inria, Post-Doctoral Fellow, until May 2019]

PhD Students

Paul Baksic [Univ de Strasbourg, PhD Student]
Jean-Nicolas Brunet [Inria, PhD Student]

Jaime Garcia Guevara [Inria, PhD Student, until Mar 2019]
Andréa Mendizabal [Univ de Strasbourg, PhD Student]
Guillaume Mestdagh [Univ de Strasbourg, PhD Student, from Oct 2019]
Sergei Nikolaev [Inria, PhD Student]
Alban Odot [Inria, PhD Student, from Oct 2019]
Raffaella Trivisonne [Inria, PhD Student, until Jun 2019]
Ziqiu Zeng [Univ de Strasbourg, PhD Student, from Jul 2019]

Technical staff

Rémi Bessard Duparc [Univ de Strasbourg, Engineer, until Sep 2019]
Mohamed Omar Boukhris [Inria, Engineer, from Feb 2019]
Frederick Roy [Univ de Strasbourg, Engineer, until Jun 2019]

Interns and Apprentices

Julia Coste Marin [Univ de Strasbourg, from Mar 2019 until Aug 2019]
Tristan Hoellinger [Inria, from Jun 2019 until Sep 2019]
Alban Odot [Inria, from Mar 2019 until Aug 2019]

Administrative Assistant

Ouiza Herbi [Inria, Administrative Assistant]

Visiting Scientist

Eleonora Tagliabue [Verona University, PhD Student, from May 2019 until Jun 2019]

External Collaborators

Rémi Bessard Duparc [IHU Strasbourg, from Oct 2019]
David Cazier [Univ de Strasbourg, HDR]
Julia Coste Marin [Univ de Strasbourg, from Sep 2019]

2. Overall Objectives

2.1. Team Overview

The MIMESIS team is developing **advanced numerical simulations** in the context of **surgical training, planning and per-operative guidance** (see Fig. 1). The underlying objectives include **patient-specific biophysical modeling**, novel **numerical techniques for real-time computation**, data assimilation using Bayesian methods and more generally **data-driven simulation**. This last topic is a transverse research theme which raises several open problems, related to the field of 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, in particular the IHU institute in Strasbourg. We also continue the development of the SOFA framework through the creation of a consortium, to better support the increasingly large community of users.

2.2. Challenges

Image-guided therapy has revolutionized medicine, in its ability to provide care that is both efficient and effective. However, images acquired during an intervention are either incomplete, under-exploited or can induce adverse outcomes. This can be due, for instance, to the lack of dimensionality of X ray images and the associated radiation exposure for the patient. We believe that by combining our expertise in real-time numerical simulation (of soft tissues, flexible medical devices, and complex interactions) with data extracted from intra-operative images, we could **provide efficient per-operative guidance**. To reach these objectives we need to solve challenges that lie at the intersection of several scientific domains. They include the **development of novel numerical strategies** (to enable real-time computation even with the increase in complexity of future models), and **data-driven simulation** (to link simulation with real world data).

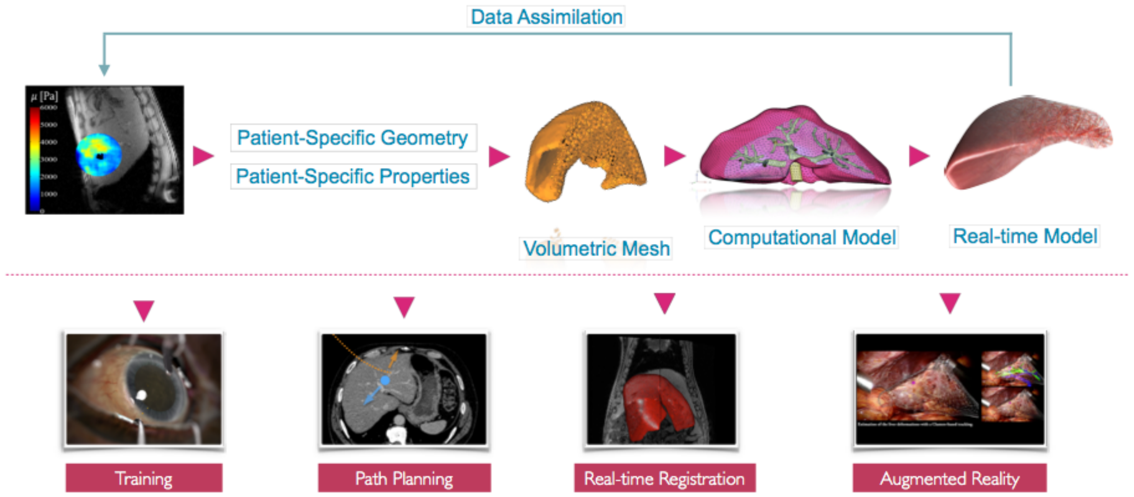

Figure 1. Data-driven simulations: from surgical training to patient-specific intra-operative computer-aided intervention.

3. Research Program

3.1. Real-time computational models for interactive applications

The principal objective of this challenge is to improve, at the numerical level, the efficiency, robustness, and quality of the simulations (see Fig. 2). An important part of our research is dedicated to the development of computational models that remain compatible with real-time computation, i.e., which allow immediate visual or haptic feedback. This typically requires computation times below $50ms$ and in some cases around $1ms$. Such advanced models can not only increase the realism of future training systems, but also act as a bridge toward the development of patient-specific solutions for computer-aided interventions. Additionally, such simulations should run on (high-end) consumer level computers (i.e. with a single multi-core CPU and a dedicated GPU). To reach these goals, we are investigating novel finite element techniques able to cope with complex, potentially ill-defined input data. After developing Smoothed FEM for real-time simulations, we are developing meshless techniques and immersed boundary methods. The first one is well suited for topological changes, which we sometimes need to account for in our simulations. The second is expected to lead to more stable, and numerically efficient, formulations of the finite element method. We are also developing numerical techniques to compute the complex interactions that can take place between anatomical structures or between medical devices and organs. Boundary conditions are known to also play an important role in the solution of such problems. Therefore we are investigating solutions to both identify and model the interactions that take place between the structure of interest and its anatomical environment.

3.2. Data-driven simulations

Data-driven simulation has been a recent area of research in our team (see Fig. 3). We have demonstrated that it has the potential to bridge the gap between medical imaging and clinical routine by adapting pre-operative data to the time of the procedure. In the areas of non-rigid registration and augmented reality during surgery, we have demonstrated the benefit of our physics-based approaches with several key publications in major conferences (MICCAI, CVPR, IPCAI, ISMAR).

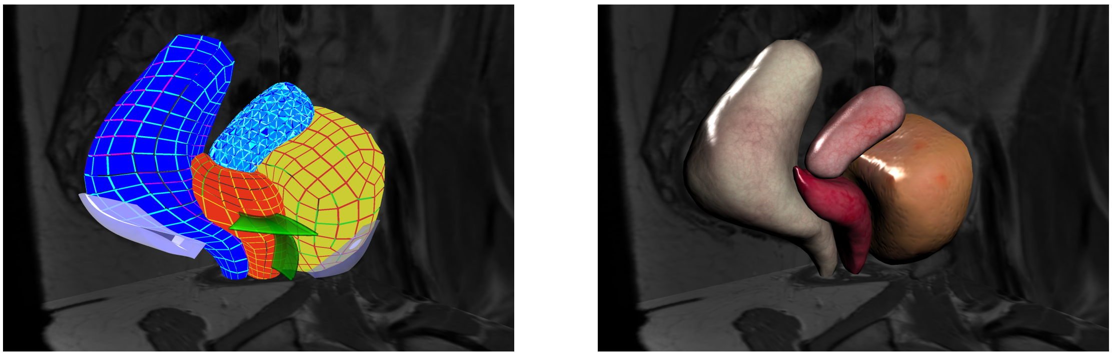

Figure 2. Model of the pelvis with (left) the finite element models of different anatomical structures and (right) their visual representations. Complex interactions take place between these deformable structures. The simulation is computed at interactive rates

We have continued this work with an **emphasis on robustness to uncertainty and outliers** in the information extracted in real-time from image data, as well as real-time parameter estimation. This is currently done by **combining Bayesian methods with advanced physics-based methods** to handle uncertainties in image-driven simulations (MICCAI 2017, CVCS 2018).

Finally, Bayesian or similar methods require to perform a large amount of simulations to sample the domain space, even when using efficient methods such as Reduced Order Unscented Kalman Filters. For this reason, we are investigating the use of neural networks to perform predictions instead of using full numerical simulations. Our latest paper [22] at MICCAI 2019 shows it is possible to **teach a neural network from numerical simulations** and **predict**, with good accuracy, **the deformation of an organ**.

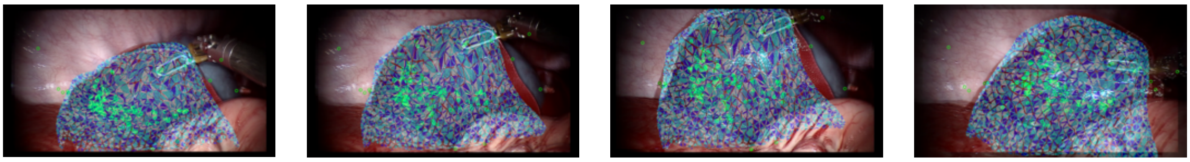

Figure 3. Real-time deformation of a virtual liver according to tissue motion tracked in laparoscopic images.

4. Application Domains

4.1. 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.

4.2. 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.

4.3. 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.

5. Highlights of the Year

5.1. Highlights of the Year

- Our paper entitled "Physics-based Deep Neural Network for Augmented Reality during Liver Surgery" was selected for oral presentation at the MICCAI conference in Shenzhen China and presented to more than 2,000 attendees [22]. In this work we demonstrated that it is possible to combine a neural network with physics-based simulation to reproduce the deformation of a complex organ.
- SOFA, our open source simulation software, continues to grow and attract scientists and companies. New results were presented during the SOFA week in November at Station F in Paris. Three start-ups created by former SOFA engineers or researchers, were among the attendees.

6. New Software and Platforms

6.1. SOFA

Simulation Open Framework Architecture

KEYWORDS: Real time - Multi-physics simulation - Medical applications

FUNCTIONAL DESCRIPTION: SOFA is an Open Source framework primarily targeted at real-time simulation, with an emphasis on medical simulation. It is mostly intended for the research community to help develop new algorithms, but can also be used as an efficient prototyping tool. Based on an advanced software architecture, it allows : the creation of complex and evolving simulations by combining new algorithms with algorithms already included in SOFA, the modification of most parameters of the simulation (deformable behavior, surface representation, solver, constraints, collision algorithm, etc.) by simply editing an XML file, the building of complex models from simpler ones using a scene-graph description, the efficient simulation of the dynamics of interacting objects using abstract equation solvers, the reuse and easy comparison of a variety of available methods.

- Participants: Christian Duriez, François Faure, Hervé Delingette and Stéphane Cotin
- Partner: IGG
- Contact: Hugo Talbot
- URL: http://www.sofa-framework.org

6.2. SofaNeedleInsertion

Needle Insertion Plugin

KEYWORD: Simulation

FUNCTIONAL DESCRIPTION: This plugin contains needle/tissue interaction models for real-time simulations of needle insertion in deformable objects using the open-source sofa frame-work. This allows for modeling the different forces playing a role during the insertion process (penetration forces, friction along the shaft...) using a constrained-based formulation. This formulation provides a fast and stable solution for the simulation of complex insertions (and reinsertion) of the needle in deformations Finite Element models

- Contact: Hadrien Courtecuisse

6.3. SOFA Optimus

Optimization methods in SOFA: stochastic filtering and data assimilation.

KEYWORDS: Data assimilation - Kalman filter - Stochastic optimization

FUNCTIONAL DESCRIPTION: Optimus is a plugin to work with advanced methods of state estimation and parameter identification. It was created to provide a testing environment for data-driven physics-based modeling (typically finite elements). While currently the plugin implements only stochastic methods based on Kalman filtering, its architecture allows for the implementation of generic prediction–correction schemes where the model is employed as a predictor and correction is performed using given observation data.

- Contact: Stéphane Cotin
- URL: https://gitlab.inria.fr/mimesis/Optimus

7. New Results

7.1. Real-time simulation of hyperelastic materials using Deep Learning

Participants: Andrea Mendizabal, Pablo Márquez-Neila, Stéphane Cotin.

The finite element method (FEM) is among the most commonly used numerical methods for solving engineering problems. Due to its computational cost, various ideas have been introduced to reduce computation times, such as domain decomposition, parallel computing, adaptive meshing, and model order reduction. In this work we propose the U-Mesh: a data-driven method based on a U-Net architecture that approximates the non-linear relation between a contact force and the displacement field computed by FE algorithm. We show that deep learning, one of the latest machine learning methods based on artificial neural networks, can enhance computational mechanics through its ability to encode highly non-linear models in a compact form. Our method is applied to three benchmark examples: a cantilever beam, an L-shape and a liver model subject to moving punctual loads. A comparison between our method and proper orthogonal decomposition (POD) is done. The results show that U-Mesh can perform very fast simulations on various geometries and topologies, mesh resolutions and number of input forces with very small errors. results were published in the Journal of Medical Image Analysis [23] (impact factor 8.5).

7.2. FEM-based confidence assessment of non-rigid registration

Participants: Paul Baksic, Hadrien Courtecuisse, Matthieu Chabanas, Bernard Bayle.

Non-rigid registration is often used for 3D representations during surgical procedures. It needs to provide good precision in order to guide the surgeon properly. We proposed in [25] a method that allows the computation of a local upper bound of the registration confidence over the whole organ volume. Using a bio-mechanical model, we apply tearing forces over the whole organ to compute the upper bound of the degrees of freedom left by the registrations constraints. Confrontation of our method with experimental data shows promising results to estimate the registration confidence. Indeed, the computed maximum error appears to be a real upper bound(see figure 4). A more advanced method was submitted at IPCAI 2020.

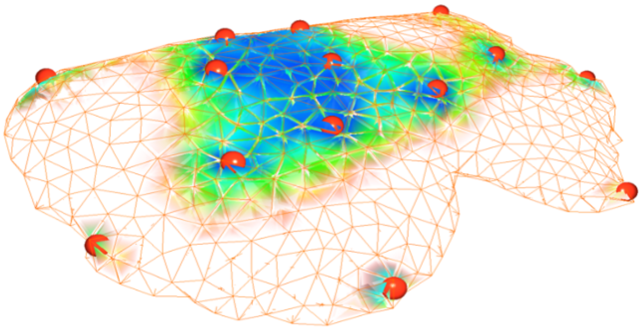

Figure 4. This is an example of confidence map given by our method on a registration of a lamb liver. The red dots are the registration constraint given by sensors. High confidence area are presented in blue. The area where the confidence is below the one needed for the surgery appears transparent.

7.3. Physics-based Deep Neural Network for Augmented Reality

Participants: Jean-Nicolas Brunet, Andrea Mendizabal, Antoine Petit, Nicolas Golse, Eric Vibert, Stéphane Cotin.

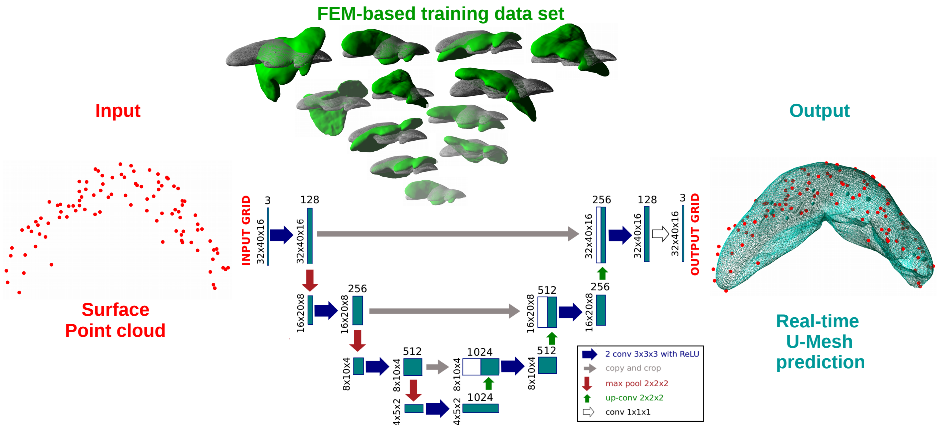

Figure 5. The U-Mesh framework allows for extremely fast simulations of soft tissues accounting for large non linear deformations.

We propose an approach combining a finite element method and a deep neural network to learn complex elastic deformations with the objective of providing augmented reality during hepatic surgery. Derived from the U-Net architecture, our network is built entirely from physics-based simulations of a preoperative segmentation of the organ (see figure 5). These simulations are performed using an immersed-boundary method, which offers several numerical and practical benefits, such as not requiring boundary-conforming volume elements. We perform a quantitative assessment of the method using synthetic and *ex vivo* patient data. Results show that the network is capable of solving the deformed state of the organ using only a sparse partial surface displacement data and achieve similar accuracy as a FEM solution, while being about 100x faster. When applied to an *ex vivo* liver example, we achieve the registration in only $3\,ms$ with a mean target registration error (TRE) of $2.9\,mm$. This results were presented at MICCAI 2019 [22].

7.4. Estimation of boundary conditions for patient-specific liver simulation during augmented surgery

Participants: Sergei Nikolaev, Stéphane Cotin.

Augmented liver surgery is an active research area that aims at improving the surgical outcome by enhancing the view of internal structures. However, to precisely estimate the position of these, an accurate model of the liver is required. While researchers have focused on proposing new models, algorithms for real-time computation or estimation of the tissue properties, very few have addressed the question of boundary conditions. Yet, they play a key role in the computation of the deformation. Boundary conditions mainly result from ligaments connecting the liver to its surrounding anatomy and limiting its motion. Unfortunately, ligaments' shapes and properties cannot be identified with preoperative imaging. We propose to estimate both the location and stiffness of ligaments by using a combination of a statistical atlas, numerical simulation, and Bayesian inference (fig. 6). Ligaments are modeled as polynomial springs connected to a liver finite element model. Their original location on the liver is based on an anatomical atlas, and their initial stiffness is taken from the literature. These characteristics are then corrected using a reduced order unscented Kalman filter based on observations taken from the laparoscopic image stream. Our approach is evaluated using synthetic data and phantom data. Results show that our estimation of the boundary conditions improves the accuracy of the simulation by 75% when compared to typical methods involving Dirichlet boundary conditions. The results were submitted for a presentation at IPCAI 2020

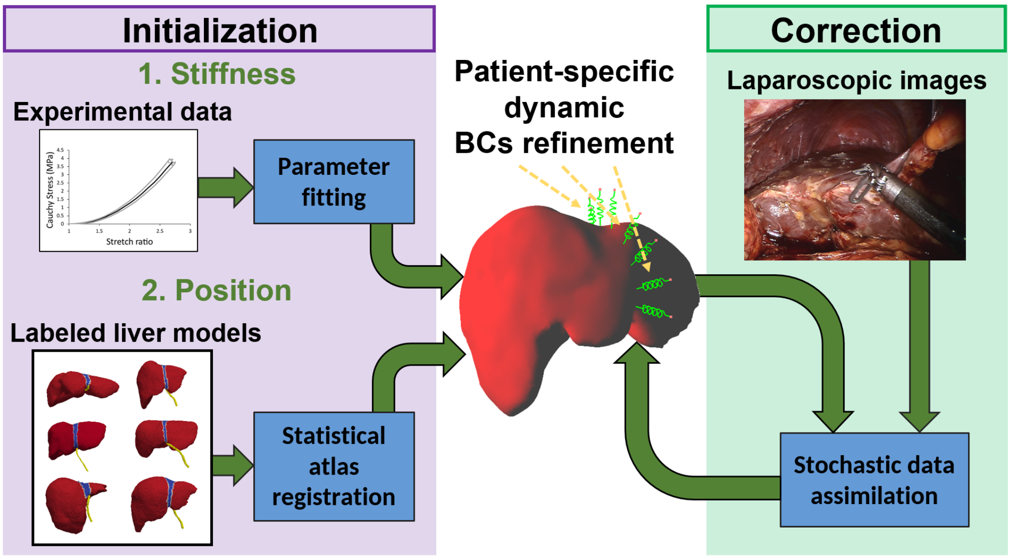

Figure 6. Overview of the boundary condition identification process. It contains two main steps. 1 - Initial approximation based on statistics from the processed model database and experimental data. 2 - Identification based on intraoperative patient-specific images.

7.5. Corotated meshless implicit dynamics for deformable bodies

Participants: Jean-Nicolas Brunet, Vincent Magnoux, Benoît Ozell, Stéphane Cotin.

We proposed a fast, stable and accurate meshless method to simulate geometrically non-linear elastic behaviors. To address the inherent limitations of finite element (FE) models, the discretization of the domain is simplified by removing the need to create polyhedral elements. The volumetric locking effect exhibited by incompressible materials in some linear FE models is also completely avoided. Our approach merely requires that the volume of the object be filled with a cloud of points (see figure 7). To minimize numerical errors, we constructed a corotational formulation around the quadrature positions that is well suited for large displacements containing small deformations. The equations of motion was integrated in time following an implicit scheme. The convergence rate and accuracy were validated through both stretching and bending case studies. Finally, results were presented using a set of examples that show how we can easily build a realistic physical model of various deformable bodies with little effort spent on the discretization of the domain. We presented our work at WSCG 2019 [21]. (Fig. 7).

7.6. The effect of discretization on parameter identification. Application to patient-specific simulations

Participants: Nava Schulmann, Igor Peterlik, Stéphane Cotin.

Identifying the elastic parameters of a finite element model from a dynamically acquired set of observations is a fundamental challenge in many data-driven medical applications, from soft surgical robotics to image-guided per-operative simulations. While various strategies exist to tackle the parameter-identification inverse problem [29], the effect of sub-optimal discretization, as often required in real-time applications, is largely overlooked. Indeed, the need to tune the parameter values in order to account for discretization-induced stiffening in specific models is reported in different works (e.g. [Chen et al., 2015, Anna et al., 2018]). However, to the best

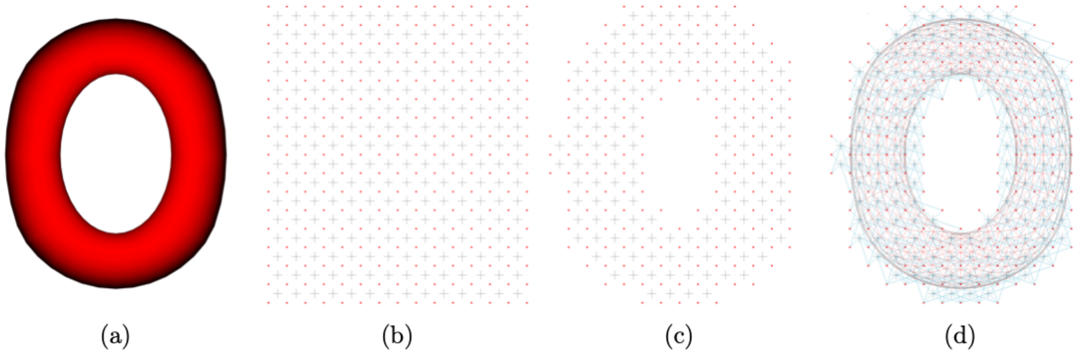

Figure 7. Volumetric discretizations of a 3D surface. (a) Surface mesh provided by the user. (b) Background grid where the grid's cubes are used to place the DOFs(degrees of freedom) and the integration points. (c) DOFs and integration points are cropped to fit the surface mesh. (d) A neighborhood of the closest particles is built around each integration point.

of our knowledge, no systematic study of this phenomenon exists to date, nor has any strategy to select optimal effective values been developed. Our work addresses the issue of parameter identification in coarsened meshes with special attention to the dynamical nature of the identification. We focus on the estimation of Young's moduli in simplified systems and show that the estimated stiffnesses are underestimated in a systematic manner when reducing the number of degrees of freedom. We also show that the effective stiffness of a given coarse mesh, when associated with an undersampled mesh discretization, is not constant but strongly depends on the prescribed deformations. These results show that the estimated parameters should not be considered as the true parameter value of the organ or tissue but instead are model-dependent values. We argue that Bayesian methods present a clear advantage w.r.t. classical minimization methods by their ability to efficiently adapt the local parameter values. The results were presented at CMBBE 2019 [26].

7.7. Elastic registration based on biomechanical graph matching

Participants: Jaime Garcia Guevara, Igor Peterlik, Marie-Odile Berger, Stéphane Cotin.

An automatic elastic registration method suited for vascularized organs is proposed. The vasculature in both the preoperative and intra-operative images is represented as a graph. A typical application of this method is the fusion of pre-operative information onto the organ during surgery, to compensate for the limited details provided by the intra-operative imaging modality (e.g. CBCT) and to cope with changes in the shape of the organ. Due differences in image modalities and organ deformation, each graph has a different topology and shape. The Adaptive Compliance Graph Matching (ACGM) method presented does not require any manual initialization, handles intra-operative nonrigid deformations of up to 65 mm and computes a complete displacement field over the organ from only the matched vasculature. ACGM is better than the previous Biomechanical Graph Matching method [3] (BGM) because it uses an efficient biomechanical vascularized liver model to compute the organ's transformation and compliance of vessel bifurcations. It allows to efficiently find the best graph matches with a novel compliance-based adaptive search. These contributions are evaluated on ten realistic synthetic and two real porcine automatically segmented datasets. ACGM obtains better target registration error (TRE) than BGM, with an average TRE in the real datasets of 4.2 mm compared to 6.5 mm, respectively. It also is up to one order of magnitude faster, less dependent on the parameters used and more robust to noise. Figure 8 depicts the large deformation and the registered porcine CBCT and CTA data. Results were published in Annals of Biomedical Engineering (2019) [4].

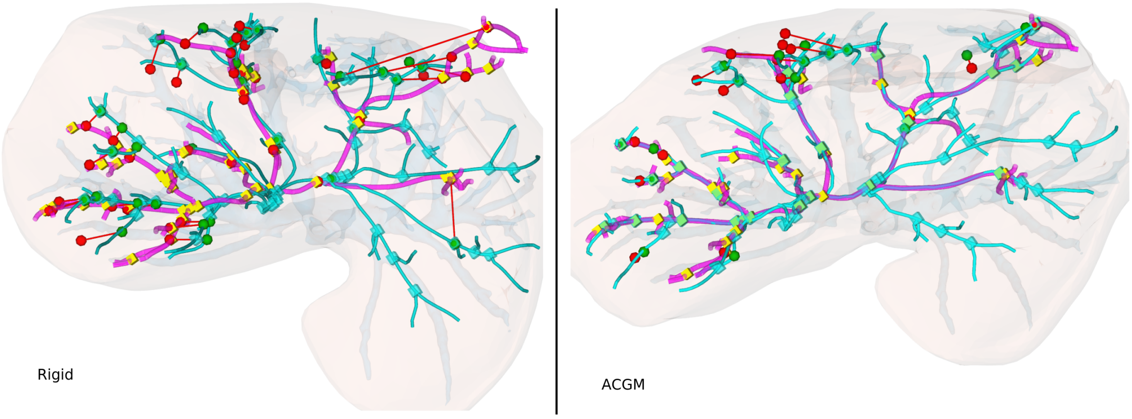

Figure 8. Registration between CTA and CBCT images. The target CBCT (in pink) and source CTA (in cyan) portal vein graphs are rendered with tubular structures. The graph nodes (bifurcations) are shown as cubic markers (in yellow for the target, cyan for the source and green for the matched). The augmented hepatic vein, which was only visible in the CTA image, is in transparent blue behind the portal veins graphs. The 37 target evaluation landmarks (red spheres) and their corresponding connected source landmarks (green spheres) and the liver structures are rigidly aligned and show the large intra-operative deformation (left image). The result of the registration process (right) shows the 16 registered landmarks.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

- **Siemens:** A global leader in healthcare industry. Via IHU, we collaborate with Siemens in the context of the IHU project CIOS Alpha Fusion dealing with augmentation of the intra-operative image provided by a fluoroscopic imaging modality with pre-operative data.
- **Naviworks:** A South Korean company specialized in ICT convergence simulation/IoT smart controlling. We collaborate on simulation and visualization in the context of interventional radiology.
- **Marion surgical**: we have continued our interactions with the start-up Marion Surgical based in Canada through the transfer of our technology related to the simulation of needle insertion.

9. Partnerships and Cooperations

9.1. Regional Initiatives

At the regional level, the MIMESIS team collaborates with

9.1.1. ICube Automatique Vision et Robotique (AVR)

We have been collaborating with the medical robotics team on percutaneous procedures, in particular robotized needle insertion (with Prof. Bernard Bayle), and needle tracking in medical images (with Elodie Breton). We are also collaborating with Jonathan Vappou on elastography.

9.1.2. ICube Informatique Géométrique et Graphique

MIMESIS joined the IGG team to collaborate in the domain of dynamic topologies, mainly through the use of the CGoGN framework. CGoGN is a C++ library for the manipulation of meshes. It implements combinatorial maps and their multiresolution extensions and has been used in various high level application like the simulation of crowds of autonomous agents and the simulation of cuts, tears and fractures in the context of surgical simulations.

9.1.3. Institute of Image-Guided Surgery (IHU)

We have several active projects and collaborations with IHU Strasbourg in order to collect and use medical images (such as MRI, CT, Fluoroscopy and Ultrasound) before, during and after minimally-invasive surgical procedures (percutaneous, endovascular and laparoscopic). Such images represent an essential support for the development of numerical simulations for intra-operative assistance through augmented and virtual reality. We also collaborate in the field of elastic registration with X-ray images and surgical training for flexible endoscopy.

9.2. National Initiatives

9.2.1. ADT (Action de Développement Technologique)

MIMESIS received a support for the development of the project **LOSAR: Liver Open Surgery with Augmented Reality** that aims at developing tools for a per-operative usage of registration algorithms developed in the team. Our goal is to be able to repeatedly test our method for one or more important publications in medical conferences. This type of publication requires to methodically repeat our solution on several patients. However, the steps are still insufficiently automated and the algorithm needs to be improved for greater reliability. These essential elements lie outside traditional research missions and require significant development and engineering effort. Indeed, an effort of automation and ergonomics will have to be made to make the use of the software sufficiently simple to be used in the operating room. Furthermore, the accuracy of the deformed model (anatomical distances modeled versus actual anatomical relationships) must also be verified and validated through experimentation. This project is done in collaboration with Paul Brousse Hospital in Paris.

9.2.2. ANR (Agence Nationale de la Recherche)

MIMESIS coordinates the ANR project entitled **SPERRY: SuPervisEd Robotic suRgerY** - application to needle insertion. Percutaneous medical procedures (using surgical needles) are among the least invasive approaches to accessing deep internal structures of organs without damaging surrounding tissues. Today, many surgical procedures rely on the use of needles allowing for complex interventions such as curie-therapies or thermo-ablations of tumors (cryoablation, radio frequencies). Unlike traditional open surgery, these approaches only affect a localized area around the needle, reducing trauma and risks of complications. These treatments also offer new solutions for tumors or for metastases for which traditional methods may be contraindicated due to the age of the patient and the extent or location of the disease. In this project, we want to develop new solutions for the control of medical robots interacting with soft tissues. This work is motivated by recent advances in the field of medical simulation achieving a sufficient level of realism to help surgeons during the operation. The maturity of these techniques now suggests the ability to use a simulation intra-operatively to control the motion of a robotic system for needle insertion. This is really a challenge, because in general, few information can be extracted in real time from images during an intervention. We believe that even minimal knowledge of the mechanical behavior of structures, associated with the use of images can make it possible and allow a robot to reach a pre-identified target during a planning stage, without human intervention.

9.2.3. Inria Collaborations

MIMESIS is closely connected to the SOFA Consortium, created by Inria in November 2015 with the objective to support the SOFA community and encourage contributions from new SOFA users. The consortium should also be a way to better answer to the needs of academic or industrial partners. MIMESIS actively participates at the development of SOFA and contributes to the evolution of the framework. Moreover, MIMESIS also participates in an initiative aiming at verification and validation of codes and algorithms of SOFA. Further, MIMESIS actively collaborates with the following Inria teams:

MAGRIT: The team at Inria Grand-Est focuses on research in computer vision and is also actively involved in computer-based solutions for the planning or the simulation of interventional radiology procedures. Currently, two PhD are co-supervised by researcher from Magrit: Jaime Garcia and Guevara Raffaella Trivisonne.

DEFROST: The team conducts research in soft robotics. We continue mutual interaction with DEFROST mainly in the context of contact modeling.

9.2.4. National Collaborations

At the national level, the MIMESIS team collaborates with:

The LML laboratory*(Laboratoire de Mécanique de Lille)*: a French research laboratory (UMR CNRS 8107) part of the Carnot institute ARTS. With more than two hundred researchers, LML focuses on the following research areas: mechanical reliability and tribology, fluid mechanics, civil engineering and soil mechanics.

Hôpital Paul-Brousse a hospital in South Paris. We collaborate with *Centre Hépato-Biliaire* via the co-supervision of the Ph.D. thesis of Nicolas Golse, MD, who is a surgeon specialized in hepatic surgery.

IRMA Research Institut on Advanced Mathematics, a research laboratory at Strasbourg university. A collaboration started in the fields of shape optimisation methods via the co-supervision of the PhD of Guillaume Mestdagh.

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

- **HiPerNav** is an Innovative Training Network (ITN) funded through a Marie Skłodowska-Curie grant. This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 722068. There is 14 fully funded and 2 partially funded PhD working on the project. The project aims to improve soft tissue navigation through research and development, to improve several bottleneck areas:
  - Creating effective pre-operative model(s) and planning
  - Faster and more accurate intra-operative model updates
  - Faster and more accurate model-to-patient registration
  - More intuitive user-interaction and effective workflow
  - Usage of high performance computing (e.g. GPU)

  From these 14 PhD students, two of them are from the Mimesis team: **Jean-Nicolas Brunet** and **Sergei Nikolaev**
- **Driven** The overall aim of the DRIVEN project is to boost the scientific excellence and innovation capacity in data-driven simulation of the University of Luxembourg (UL) and partners (Inria, University of Limerick, and University of Texas at Austin). To boost their scientific excellence and technology transfer capacity in data-driven simulation, the partners will implement a research and innovation strategy focused on three sub-topics:
  - Mathematical foundations for data-driven simulations – UL with UT Austin,
  - Data-driven simulations for computer-assisted therapy – UL with Inria,
  - Data-driven simulations for functional composite materials –UL with ULIM.

9.4. International Initiatives

9.4.1. Informal International Partners

- **CAMERA group, University of Bath, UK:** Collaboration on non-rigid registration using **RGB-D** sensors
- **PRISMA Lab, University of Naples, Italy:** Collaboration on soft object robotic manipulation, along with DEFROST team at Inria Lille, and collaboration on visual perception for robotic surgery.
- **University of Twente, Netherlands:** we collaborate with Prof. Stefano Stramigioli, head of a group in Robotics and Mechatronics laboratory, on the development of a low-cost training system for flexible endoscopy.
- **Verona University, Italy:** we collaborate with the ALTAIR Robotics Lab on computer-aided ultrasound guidance using real-time registration. This resulted in 2 publications this year: [19] and [23].
- **Faculty of Informatics, Masaryk University, Czech Republic:** We collaborate on simulation of living cells in fluorescent microscopy.
- **Team Legato, University of Luxembourg:** We have an active collaboration with Prof. Stéphane Bordas on error estimation in real-time simulations of deformable objects.
- **ARTORG Center for Biomedical Engineering Research, Bern, Switzerland:** Collaboration in the projects related to deep learning.
- **CIMIT and Harvard Medical School:** we collaborate with members of the Center for Minimally Invasite Therapy and faculty from HMS on the development of a training system for Resuscitative endovascular balloon occlusion of the aorta (REBOA).

9.5. International Research Visitors

Eleonora Tagliabue, PhD student at the robotics laboratory of Verona University, visited the team from April to June 2019. During her stay we collaboration of the comparison of different physics-based approaches to model soft tissues. This led to a publication in the International Journal of Computer Assisted Radiology and Surgery. We also applied our deep physics network to the problem od registration of breast model onto ultrasound data. This was presented at the MICCAI workshop on Computational Biomechanics in September 2019.

9.5.1. Visits to International Teams

Jean-Nicolas Brunet and Sergei Nikolaev spent 2 weeks in Forchheim (Germany) to visit Siemens R&D and product development groups, as part of the H2020 HiPerNav project.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Reviewer - Reviewing Activities

Members of the teams regularly provide reviews for:

- International conferences and journals on Image Processing and Computer-Assisted Interventions (MICCAI, IPCAI, IJCARS, Medical Image Analysis, Transactions on Medical Imaging)
- International conferences and journals on Computer Graphics and Physics-based modeling (Eurographics, VRIPHYS)
- International conferences on Robotics (IROS, ICRA, EuroHaptics)

10.1.2. Invited Talks

- **Nava Schulmann**: talk on "Bayesian data assimilation" at the Data-driven computational mechanics workshop, New York (USA), February 2019.
- **Hadrien Courtecuisse**: Next Generation Intelligent Surgical Systems workshop, Verona (Italy), November 2019
- **Stéphane Cotin**: Next Generation Intelligent Surgical Systems workshop, Verona (Italy), November 2019
- **Stéphane Cotin**: International Conference on Nonlinear Solid Mechanics, Roma (Italy), June 2019.
- **Stéphane Cotin**: talk on "Digital Twin for medicine" at the Data-driven computational mechanics workshop, Luxembourg, September 2019
- **Stéphane Cotin**: talk on "Patient-specific simulation in medicine" at the Data-driven computational mechanics workshop, February 2019.

10.1.3. Scientific Expertise

Stéphane Cotin provides scientific expertise for Insimo (www.insimo.com).

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

- Master: Igor Peterlik, Modélisation des systèmes vivants, 17h, M2, University of Strasbourg
- Master: Igor Peterlik, Visualisation des données et simulation, 10h, M1, University of Strasbourg
- Master: Hadrien Courtecuisse, Real time simulation, 30h, M2, University of Strasbourg
- Master: Hadrien Courtecuisse, Visualisation des données et simulation, 10h, M2, University of Strasbourg
- Master: Hadrien Courtecuisse, Visualisation des données et simulation, 10h, M1, University of Strasbourg

10.2.2. Supervision

PhD : Jaime Garcia Guevara, Augmented ultrasound imaging for hepatic surgery, supervised by Stéphane Cotin, Marie-Odile Berger. Defended on Dec 2nd 2019.

PhD in progress: Raffaella Trivisonne, Computer-aided vascular interventions, started 01/09/2015, supervised by Stéphane Cotin and Erwan Kerrien.

PhD in progress: Nicolas Golse, Navigation using the augmented reality during hepatic surgery, started 01/09/2016, supervised by Stéphane Cotin.

PhD in progress: Sergei Nikolaev, Characterization of boundary conditions for biomechanical modeling of liver, started 01/05/2017, supervised by Stéphane Cotin, co-supervised by Igor Peterlik and Hadrien Courtecuisse.

PhD in progress: Jean-Nicolas Brunet, Characterization of boundary conditions for biomechanical modeling of liver, started 01/09/2017, supervised by Stéphane Cotin.

PhD in progress: Andrea Mendizabal, Numerical simulation of soft tissues and machine learning, 01/09/2017, supervised by Stéphane Cotin.

PhD in progress: Paul Baksic, Robotic assistance for percutaneous surgical interventions in deformable structures – Application to radiofrequency ablation, started 01/10/2018, supervised by Hadrien Courtecuisse.

PhD in progress: Ziqiu Zeng started 01/07/2019, SPERRY - Supervised Robotic Surgery - Application to needle insertion, supervised by Hadrien Courtecuisse.

PhD in progress: Guillaume Mestdagh, started 01/09/2019, Real-Time Tumor Tracking as an Optimization Problem, co-supervised by Stéphane Cotin.

10.2.3. Juries

Stephane Cotin was president of the Ph.D. committee for Lorenzo Sala (September 27, 2019). Mathematics laboratory, Strasbourg

Stephane Cotin was in the Ph.D. committee for Jaime Guevara (December 2, 2019). LORIA, Nancy.

10.3. Popularization

10.3.1. Articles and contents

Stephane Cotin wrote a chapter for the book entitled "Virtual Reality and Augmented Reality - Myths and Realities", which is an easy access book on the usages and developments of Virtual Reality and Augmented Reality for various domains. ISBN 978-1-78630-105-5.

10.3.2. Education

We are developing a training system dedicated to flexible endoscopy, used in university diplomas and masters programs for clinicians.

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