Activity Report 2018

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

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Computer Science and Digital Science:

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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

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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 ICube laboratory and the IHU institute. We also collaborate with members of Inria Nancy, Inria Lille, Ecole Centrale de Lille, University of Luxembourg, Karlsruhe Institute of Technology, TIMC Laboratory in Grenoble, Twente University in the Netherlands, SINTEF in Norway, ARTOG in Bern. 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).

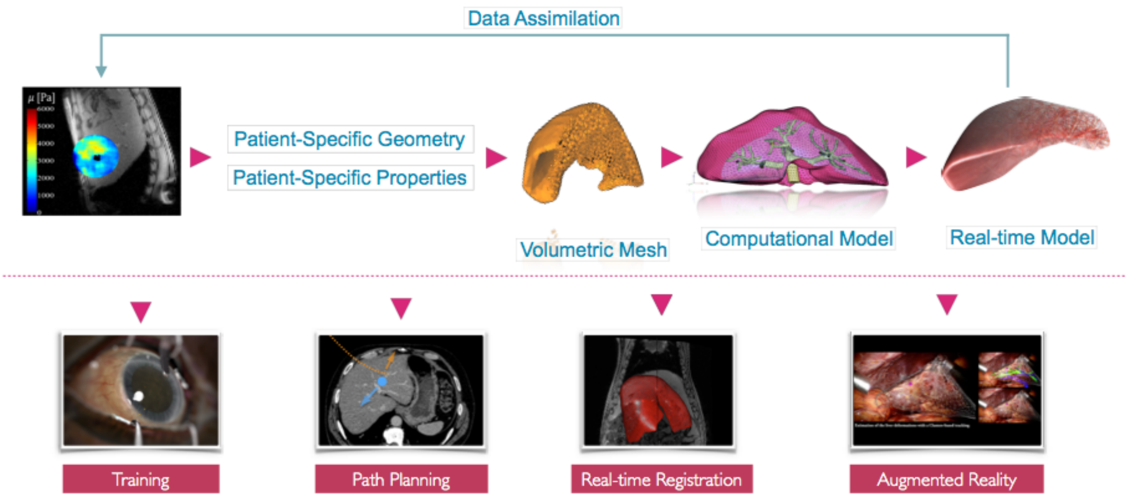

Figure 1. Patient-specific simulations: from training to intra-operative guidance.

3. Research Program

3.1. Real Time Patient-Specific Computational Models

The principal objective of this challenge is to improve, at the numerical level, the efficiency, robustness, and quality of the simulations (see Fig. 2). To reach these goals, we will investigate 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 also 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 will also propose numerical techniques such as domain decomposition and model order reduction, to handle real-time computation on more complex geometries or constitutive models. Boundary conditions are know to also play an important role in the solution of such problems. Therefore we are developing solutions to both identify and model the interactions that take place between the structure of interest and its anatomical environment.

3.2. Data-driven Simulation

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) and awards (best paper [25] at ISMAR 2013, second best paper [26] at IPCAI 2014).

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).

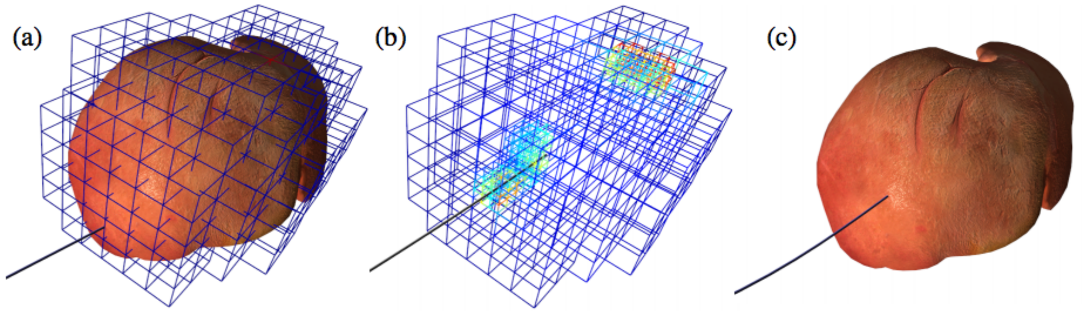

Figure 2. (a) Simulation of needle insertion in a liver; (b) Using dynamic mesh refinement scheme driven by error estimate; (c) Visual depiction. The simulation runs at 22 Hz using a PC with 4 GHz CPU.

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 [5] at MICCAI 2018 shows it is possible to **teach a neural network from numerical simulations** and **predict, with high accuracy, the relationship between an image** of the anatomy and **the associated force**.

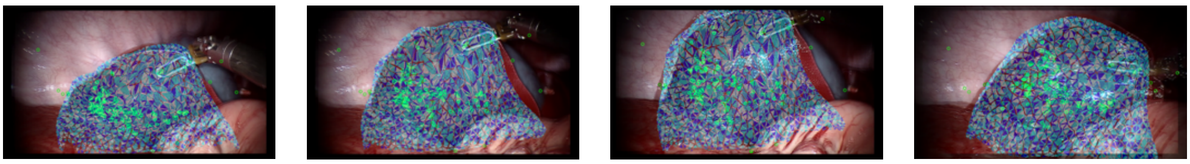

Figure 3. Real-time deformation of a virtual liver according to tissue motion tracked in laparoscopic images.

4. Application Domains

4.1. Surgical Training

Virtual training prevents medical students from early manipulation of real patients. The development of simulation used for medical training usually requires important computational power, since realistic behaviours 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 Navigation

Besides the surgery training and planning, another major need from clinicians is surgical guidance. While the practician 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 tumour 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

5.1.1. Awards

Stéphane Cotin received the Inria – French Académie des Sciences – Dassault Systèmes Innovation Award. The committee underlined the professional experience of Stéphane Cotin at the cutting edge of research into numerical simulation. "*Stéphane Cotin is leading the MIMESIS team, working in close collaboration with IHU Strasbourg since its creation in 2014. Besides the development of SOFA, the team is mainly dedicated to real-time simulation in operating theaters. Its flagship projects include the development of 3D models that are to be projected on the livers of patients having a tumour removed, or the development of highly realistic virtual images that would improve interventional radiology techniques by limiting exposure to X-rays.*"

Andrea Mendizabal received the Student Travel Award at MICCAI 2018 Granada. Spotlight presentation on the paper *A Combined Simulation & Machine Learning Approach for Image-based Force Classification during Robotized Intravitreal Injections*.

Fanny Morin and Yinoussa Adagolodjo received their PhD with awards respectively in October 2017 and September 2018.

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: Stéphane Cotin
- URL: http://www.sofa-framework.org

6.2. SofaCV Plugin

Keywords: Simulation - Visualization - Image processing
Functional Description: SofaCV is a plugin for the simulation framework SOFA. Its purpose is to provide computer vision tools to SOFA. More specifically, its goal is to enable the use of SOFA simulations in augmented reality, and virtual reality applications. The SofaCV plugin is not a standalone plugin by itself. Instead it provides an API for submodules (mainly Sofa's ImageProcessing and DataAcquisition plugin) such as base datatypes, Python bindings, SofaQtQuick widgets etc, along with some utility SOFA Components to read, write or display an image in the scene view.

The ImageProcessing plugin is a plugin for the simulation framework SOFA. Its purpose is to provide general purpose Computer vision features to Sofa. More specifically, its goal is to enable the use of SOFA simulations in augmented reality, and virtual reality applications. The ImageProcessing plugin depends on the SofaCV Base plugin. The ImageProcessing plugin doesn't have the ambition to provide cutting-edge computer vision algorithms, but instead, wraps OpenCV's features while taking advantage of SOFA's Component-based API. This plugin also provides useful Camera components, providing on-the-fly conversions from/to OpenGL & OpenCV's camera calibration parameters. (calibrating cameras, modifying both intrinsic and extrinsic camera parameters in OpenGL)

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6.3. Needle Insertion Plugin

Keywords: Simulation - Needle insertion - Haptic feedback
Functional Description: This plugin contains needle/tissue interaction models for real time simulations of needle insertion in deformable objects using the open-source sofa framework. 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 deformable Finite Element models.

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6.4. Optimus Plugin

Keywords: Simulation - Stochastic Filtering - Data Assimilation - State Estimation - Medical applications
Functional Description:

The goal of the plugin is to implement a real integration of Verdandi in SOFA in order to provide a complex and efficient tool for data-assimilation and state-estimation based on filtering prediction-correction scheme.

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- Collaborators: Sergei Nikolaev, Nava Schulmann, Raffaella Trivisonne
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6.5. RGBDTracking Plugin

Keywords: Simulation - RGBD data Processing - Object tracking - data fusion - Numerical simulations
Functional Description: RGBDTracking is a SOFA plugin to register and track deformable objects in real-time using an RGB-D sensor. This frame-by-frame system relies on a prior visual segmentation of the object in the RGB image. The resulting segmented point cloud is then used to register the object, first in a rigid manner, and then by non-rigidly fitting the known mesh, based on the Finite Element Method to model elasticity, and on vision-based external forces exerted on the mesh.

- Author: Antoine Petit
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7. New Results

7.1. A Unified Bayesian and Physics-Based Approach for Non-rigid 3D Shape Reconstruction from 2D Images

We developed a method to reconstruct the 3D shape of the interventional device, based on a constrained physics-based simulation combined with 2D monocular fluoroscopic images through a Bayesian filter (see Fig. 4). Whereas the physics-based model provides a prediction of the device shape within the blood vessel, taking into account non-linear interactions between the catheter and the surrounding anatomy adds further information on its current position. In addition, an Unscented Kalman Filter is used to combine the navigation model with the 2D external observations. We focused on a medical application as we believe the method could provide an actual solution to some of the current limitations of fluoroscopy-based procedures. The use of a Bayesian formalism allows for retrieving a good estimate in presence of ambiguous views (i.e. in presence of overlapping anatomies) and to take into account uncertainties on the prediction model (errors in constraint definition, as well as inaccuracies in the mechanical characterization of the catheter) and errors in the external measurements.

The method has been implemented through software developed within the team; for more details see sec. 6.4 and 6.3. Validation has been performed on porcine in-vivo data, acquired in accordance with UE norms, in collaboration with Pr. Mario GIMENEZ and Dr. Alain GARCIA from IHU-Strasbourg.

- *Authors:* Raffaella Trivisonne and Stéphane Cotin and Erwan Kerrien
- *Type:* PhD Thesis

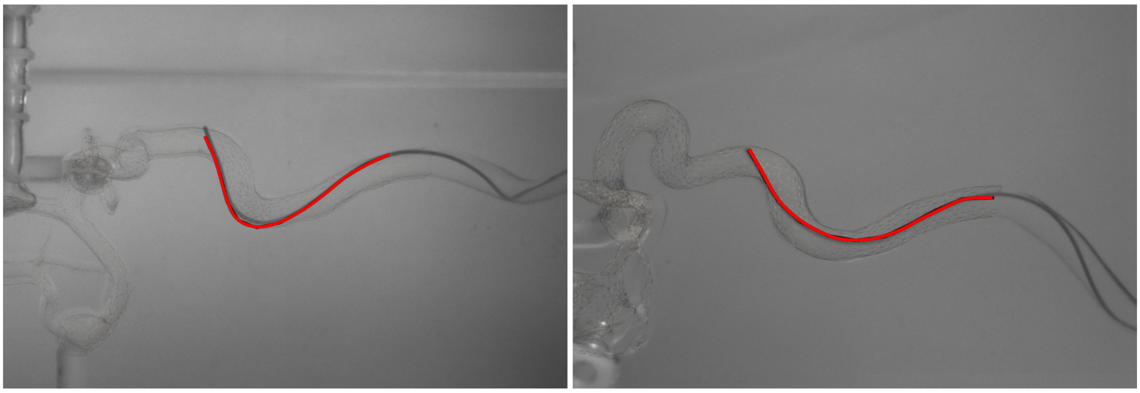

Figure 4. Catheter reconstruction in acquisition view (left) and validation view (right)

7.2. Biomechanics-based graph matching for augmented CT-CBCT

Augmenting intraoperative cone beam computed tomography (CBCT) images with preoperative computed tomography (CT) data in the context of image-guided liver therapy is proposed (see Fig. 5). The expected benefit is an improved visualization of tumor(s), vascular system and other internal structures of interest. An automatic elastic registration based on matching of vascular trees extracted from both the preoperative and intraoperative images is presented. Although methods dedicated to non-rigid graph matching exist, they are not efficient when large intraoperative deformations of tissues occur, as is the case during the liver surgery. First, an improved graph matching algorithm using Gaussian process is introduced by imposing additional constraints during the matching when the number of hypotheses is large; this extended version does not require a manual initialization of matching. Second, a fast biomechanical model is employed to make the method capable of handling large deformations. The proposed automatic intraoperative augmentation is evaluated on both synthetic and real data. It is demonstrated that the algorithm is capable of handling large deformations, thus being more robust and reliable than previous approaches. Moreover, the time required to perform the elastic registration is compatible with the intraoperative navigation scenario. The input data and result of the biomechanics-based graph matching method, which can handle large deformations and augment intraoperative CBCT, is shown in Fig. 5 .

- *Authors:* Jaime Garcia Guevara and Igor Peterlik and Marie-Odile Berger and Stephane Cotin
- *Type:* Journal publication IJCARS 2018

7.3. A Combined Simulation and Machine Learning Approach for Force Classification during Robotized Intravitreal Injections

Intravitreal injection is one of the most common treatment strategies for chronic ophthalmic diseases. The last decade has seen the number of intravitreal injections dramatically increase, and with it, adverse effects and limitations. To overcome these issues, medical assistive devices for robotized injections have been proposed and are projected to improve delivery mechanisms for new generation of pharmacological solutions. In our work, we propose a method aimed at improving the safety features of such envisioned robotic systems. Our vision-based method uses a combination of 2D OCT data, numerical simulation and machine learning to estimate the range of the force applied by an injection needle on the sclera (see Fig. 6). We build a Neural Network (NN) to predict force ranges from Optical Coherence Tomography (OCT) images of the sclera directly. To avoid the need of large training data sets, the NN is trained on images of simulated deformed

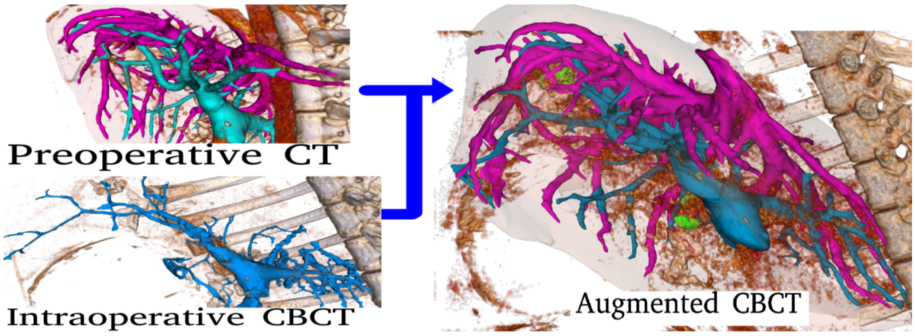

Figure 5. In the top left the preoperative CT image with complete portal and hepatic vessels clearly visible. In the bottom left the intraoperative deform, noisy CBCT image with partial only partial portal vessels visible. In the right the augmented CBCT view with the complete vessels added form preoperative image.

sclera. We validate our approach on real OCT images collected on five *ex vivo* porcine eyes using a robotically-controlled needle. Results show that the applied force range can be predicted with 94% accuracy. Being real-time, this solution can be integrated in the control loop of the system, allowing for in-time withdrawal of the needle.

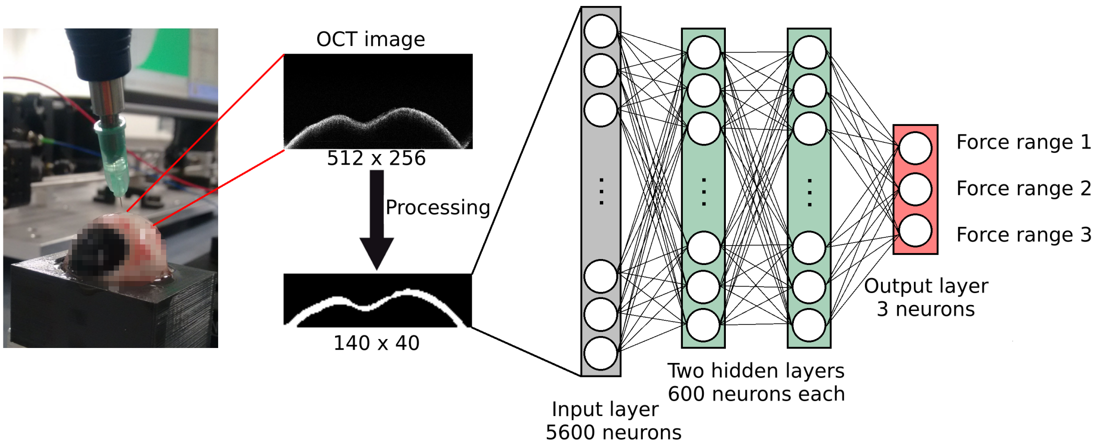

Figure 6. During the robotized intravitreal injection an OCT image of the deformed sclera is collected. The obtained image is processed and given a to a Neural Network that predicts the force range of the force applied by the robotically guided needle.

- *Authors:* Andrea Mendizabal and Stephane Cotin
- *Type:* Conference publication MICCAI 2018

7.4. Inverse simulation for Robotic control of needle insertion

We recently published in a numerical method allowing for automatic control of a robot during needle insertion procedures (see Fig. 7). Our approach is to develop control models allowing for the correction and prediction of the deformation of structures (needle, tissues or the robot itself) and to adapt the behavior of the robot in order to reach an objective. We showed that inverse steps can be used to control an articulated robot while considering deformations of structures during needle insertion. The method has been used for a needle insertion inside a polyurethane foam using a Mitsubishi RV1A anthropomorphic robot arm. During the insertion vertical and lateral deformations were generated (see Fig. 7) leading to significant modification of the undeformed trajectory, important bending of the needle and even an off-plane shift between the base of the needle and the insertion point. Despite these strong modifications, the method was able to maintain the tip of the needle within the thickness of 1 cm of the foam and followed the desired curved path with accuracy lower than 1 mm without any human intervention.

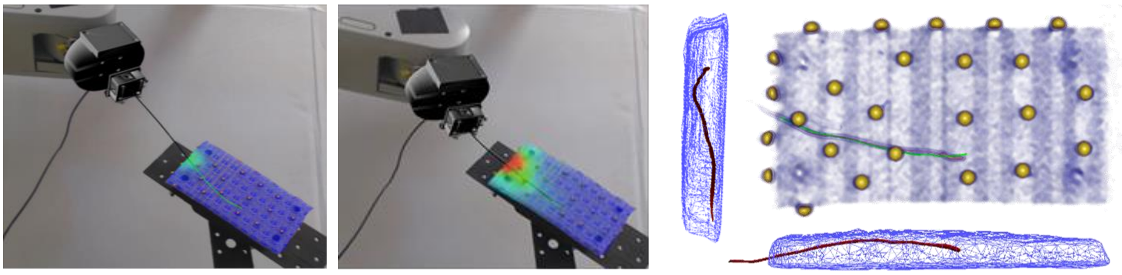

Figure 7. Robotic control based on inverse finite element simulations for needle insertion in deform-able structures. The models are registered in real-time using makers and infrared image-tracking system. We measured an average distance of 1.2 mm between needle's (red) and the desired trajectory (green).

7.5. Marker-Based Registration for Large Deformations

We proposed an Augmented Reality (AR) system for open liver surgery (see Fig. 8). Although open surgery remains the gold-standard for the treatment of complex tumors and central lesions, technological issues actually prevent using AR with sufficient accuracy for clinical use. We propose a markers-based method allowing for the tracking and the deformation of a preoperative model in real-time during the surgery. Markers are manually placed on the surface of the organ after opening the abdominal cavity, and tracked in real-time by a set of infrared cameras. Our framework is composed of both a non-rigid initial registration method, providing an estimation of the location of the markers in the preoperative model, and a real-time tracking algorithm to deform the model during the surgery (even for large deformation or partial occlusion of the organ). The method is validated on both synthetic and ex-vivo samples; in addition, we demonstrate its applicability in the operating room during a liver resection surgery on a human patient. Preliminary studies provided promising results to improve the location of tumors, and to help surgeons into planning the ideal resection intraoperatively.

- *Authors:* Yinoussa Adagolodjo, Nicolas Golse, Eric Vibert, Michel De Mathelin, Stéphane Cotin, Hadrien Courtecuisse
- *Type:* PhD Thesis, publication to ICRA

7.6. Automatic and robust 2D/3D registration on fluoroscopic images

We introduce a unified solution to detect, register and track the liver in 2D live fluoroscopic X-ray images, in order to provide augmented reality and guidance during surgery (see Fig. 9). The solution can be decomposed

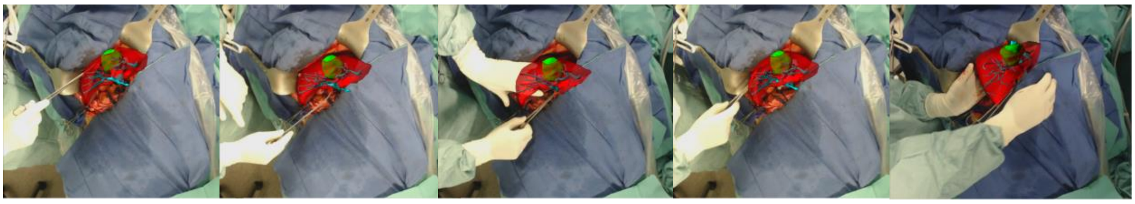

Figure 8. Figure 3: Research prototype for Augmented Reality during open surgery of the liver. We pro-posed a method based on markers for the registration of a preoperative model in real time during surgery. The markers are placed manually on the surface of the body after the opening of the abdominal cavity, and followed in real time by a set of infrared cameras.

into two phases, with an initial phase to globally estimate the rigid pose through template matching, and a second local rigid refinement step. A main contribution lies in the combination, for the pose refinement step, of intensity and contour based features over the contrasted vessels of the liver and surrounding organs, by integrating corresponding visual cues in a local optimization framework with respect to the pose. The method does not need any 2D segmentation of the contrasted vessels but relies on a synthetic X-ray rendering algorithm, and requires very few assumptions or priors. Our solution has been tested on synthetic and porcine data, showing its efficiency on realistic scenarios.

A non-rigid registration technique to account for local deformations of the target is also investigated. Once the model is rigidly aligned, local estimation of the deformations undergone by the vasculature and the parenchyma, given a linear or volumetric elastic deformation model of the vessels and the parenchyma, driven by local optical flow features.

The method has been implemented through software developed within the team; for more details see sec. 6.4-6.3. Validation has been performed on porcine in-vivo data, acquired in accordance with UE norms, in collaboration with Pr. Mario GIMENEZ and Dr. Alain GARCIA, Pr. Federico Davrieux, and Pim Hendriks, Daan Kuppens and from IHU-Strasbourg.

- *Authors:* Antoine Petit, Bruno Marques, Stéphane Cotin
- *Type:* Submission to IPCAI 2019

7.7. Capturing Deformations of Interacting Soft Objects Using RGB-D Data

We present a method for tracking multiple interacting deformable objects undergoing rigid motions, elastic deformations and contacts, using images and point cloud data provided by an RGB-D sensor (see Fig. 10). A joint registration framework is proposed, based on physical Finite Element Method (FEM) elastic and interaction models. It first relies on a visual segmentation of the considered objects in the RGB images. The different segmented point clouds are then processed to estimate rigid transformations with on an ICP algorithm, and to determine geometrical point-to-point correspondences with the meshes. External forces resulting from these correspondences and between the current and the rigidly transformed mesh can then be derived. It provides both non-rigid and rigid data cues. Classical collision detection and response model is also integrated, giving contact forces between the objects. The deformations of the objects are estimated by solving a dynamic system balancing these external and contact forces with the internal or regularization forces computed through the FEM elastic model. This approach has been here tested on different scenarios involving two or three interacting deformable objects of various shapes, with promising results.

A case study in open surgery on the liver has also been investigated. Yet in this case a major improvement in the accuracy of the registration is provided by the integration of anatomical shape constraints, which are naturally hidden from the RGB-D camera, and that we account for through a registration with the pre-operative

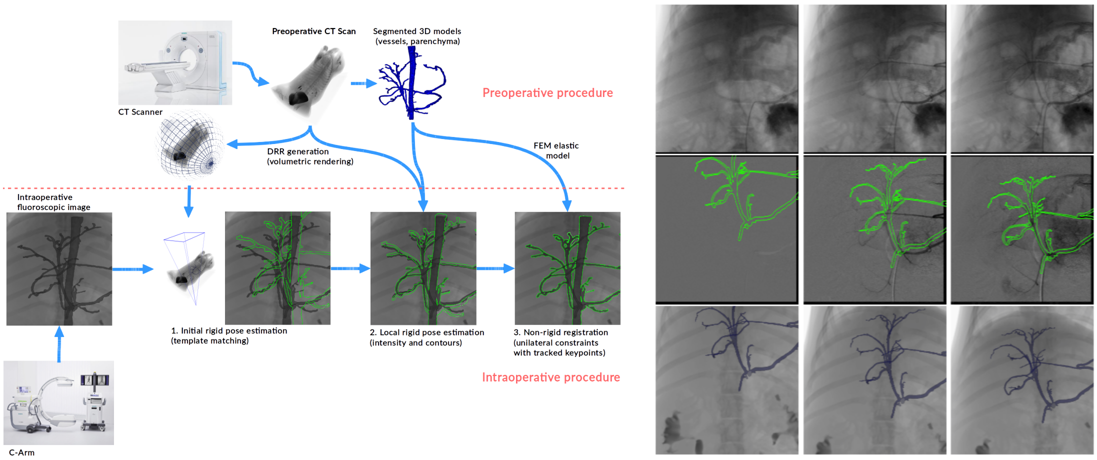

Figure 9. Pipeline of the system and results of the rigid registration system.

CT data. With a comparative study, we demonstrate the relevance of our method in a real-world application mimicking an open surgery scenario where the liver has to be tracked to provide an augmented reality view.

The method has been implemented through software developed within the team, especially the RGBDTracking plugin. 6.4 and 6.3. Validation has been performed on porcine in-vivo data, acquired in accordance with UE norms, in collaboration with Pr. Mario GIMENEZ and Dr. Alain GARCIA, Pr. Federico Davrieux, and Pim Hendriks, Daan Kuppens and from IHU-Strasbourg.

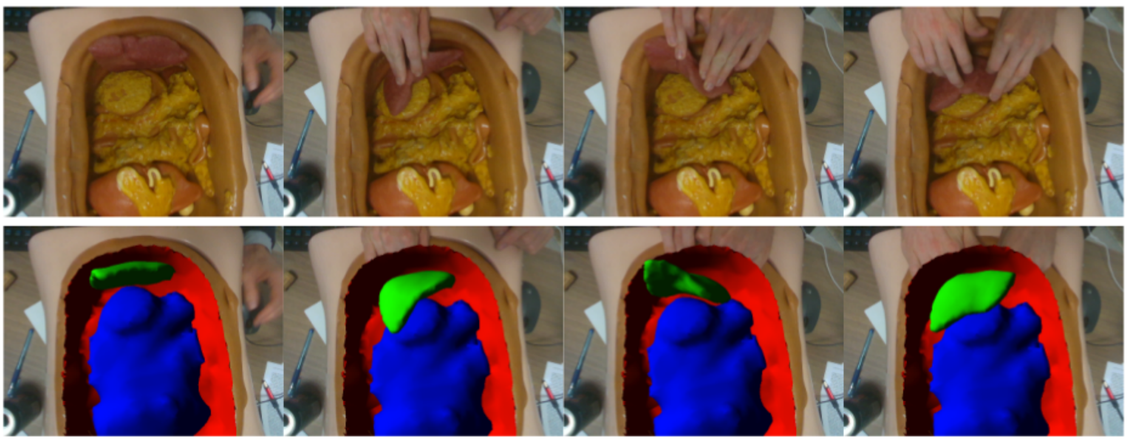

Figure 10. Pipeline of the system and results of the rigid registration system.

- *Authors:* Antoine Petit, Stéphane Cotin
- *Type:* Publications to IROS 2018 and ACCV Workshops 2018

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

- **Altran:** A global leader in innovation and high-tech engineering consulting, Altran accompanies supports its clients in the creation and development of their new products and services. We have a common history of successful collaboration via CIFRE Ph.D. thesis of Rosalie Plantefève.
- **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.

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 (IGG)

MIMESIS joined the IGG team and develops collaboration 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) Strasbourg

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. Eventually, simulations will be used for the diagnostic, treatment as well as for training and teaching in medical domain. Yet, before being used in current clinical routine, such simulations must be validated on animal models. Through our collaboration with IHU, we use CT and MRI images to retrieve the anatomical model of internal structures, whereas fluoroscopic and ultrasound images can be used to retrieve 2D images of the physiology and the navigation of surgical instruments within the anatomy. In-vivo procedures can also be performed under ethical approval of MSER (reference to ethic protocol *APAFIS #15433-2018060815283960*). We also collaborate with IHU-Strasbourg fellow surgeons, such as Pr. Mario GIMENEZ and Dr. Alain GARCIA, that provide medical and technical support for medical aspects (see Fig. 11).

- *Authors:* Raffaella Trivisonne, Stéphane Cotin

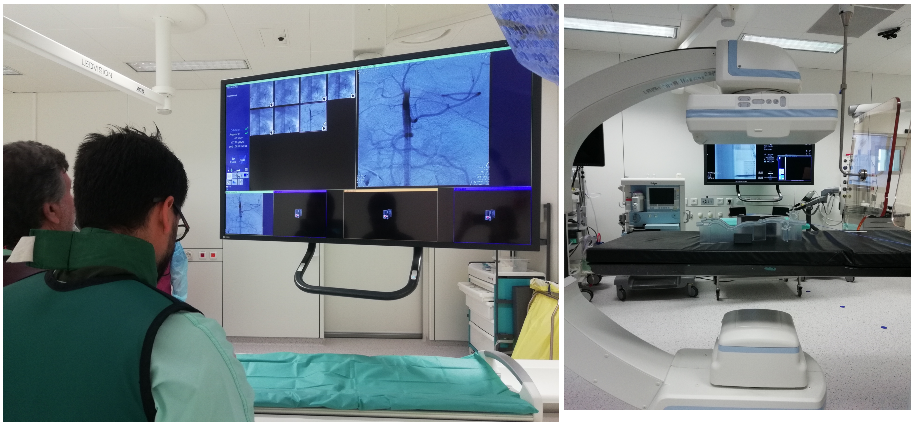

Figure 11. Environmental Set-Up for Image Acquisition. IHU-Strasbourg Platform.

9.2. National Initiatives

9.2.1. ADT (Action de Développement Technologique)

Team 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 research algorithms developed in the team. Although the current trend is to move towards minimally invasive surgery, open-liver surgery remains the standard treatment for most patients. For Augmented reality purpose, open surgery raises specific constraints compared to celioscopic surgery, such as larger deformations of the liver and unavoidable occlusions of the organ. During the year 2017, the Mimesis team has developed an augmented reality prototype for open liver surgery. This prototype was developed as part of research projects and a collaboration between the team Mimesis and the CHB Paul Brousse (first service of hepatobiliary surgery in France).

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.

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 thermoablations of tumors (cryoablation, radio frequencies). Unlike traditional open surgery, these approaches only affect a localized area around the needle reducing this way 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. Although they provide very good results, these interventions significantly increase the level of expertise required for practitioners.

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. These simulations are now used for training of surgeons, and even for visual assistance during the operation thanks to augmented reality. The maturity of these techniques now suggests the ability to use a simulation intraoperatively to control the motion of a robotic system for needle insertion. This is really a challenge, because in general, very 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 contributed 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, with a strong collaboration with the CHU in Nancy. We collaborate with MAGRIT in the area of interventional radiology and augmented reality. Currently, two PhD thesis are co-supervised by researcher from Magrit: the PhD thesis of Jaime Garcia Guevara and 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 TIMC laboratory*(Techniques de l'Ingénierie Médicale et de la Complexité)* in Grenoble: this large research group has a strong background in computer-aided surgery, medical imaging, registration, statistical and bio-mechanical modeling. We have regular interactions with various members of this group. We are collaborating with Yohan Payan (DR CNRS) on the modeling and simulation of the brain shift. A common PhD thesis started on that topic in late 2014. Other areas of interest are in the field of advanced soft tissue modeling and computer aided surgery.

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 at the center.

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

- **HiPerNav** (https://hipernav.eu) 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's 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** ((https://driven.uni.lu/) 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 its high-quality Twinning partners: Institut National de Recherche en Informatique et en Automatique (Inria), University of Limerick (ULIM) and University of Texas at Austin (UT Austin). To achieve this aim, the 3 year project will build upon the existing strong research and innovation base of UL and its Twinning partners. The recently established Computational Sciences interdisciplinary group is composed of members from different research units and disciplines as diverse as Earth Sciences, Life Sciences, Physics, Mathematics and Engineering, with the common goal to set up a network among application-driven scientists which can provide interdisciplinary expertise in the field and contribute to this platform of training and knowledge exchange. 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:
  1. Mathematical foundations for data-driven simulations – UL with UT Austin,
  2. Data-driven simulations for computer-assisted therapy – UL with Inria, and
  3. 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 - Antoine Petit
- **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 - Antoine Petit.
- **University of Twente, Netherlands:** Thanks to our clinical partner IHU, we collaborate with Prof. Stefano Stramigioli, head of a group at Robotics and Mechatronics laboratory.
- **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.

9.5. International Research Visitors

9.5.1. Internships

Domenico Idone (master student from Italy) did a six month internship in the team. The aim of the training period is to investigate a novel method to track catheter shape and location during vascular interventions. We have already experimented the use of a fiber optic, equipped with Fiber Bragg Grating sensors, embedded on a flexible plate, to determine its shape. This sensing system has allowed us to track the motion of the plate undergoing a two-dimensional deformation. The objective of this internship is to expand this work to the case of a three-dimensional deformation, which requires significant improvements over the previous approach.

Renée Geraats (Twente university) did a 2 months internship. She investigated different visualization solutions for augmented reality on fluoroscopic images of the liver and its vasculature, for the 2D3D Fusion project.

Daan Kuppens (Twente university) did a 2 months internship. He provided support on the acquisition of reliable porcine CT and X-ray fluoroscopic images fluoroscopic images, on CT segmentation of the liver and its vasculature and on clinical applications, for the 2D3D Fusion project.

Pim Hendricks (Twente university) did a 2 months internship. She provided support on the acquisition of reliable porcine CT and X-ray fluoroscopic images fluoroscopic images, and on clinical applications, for the 2D3D Fusion project.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. Reviewing Activities

Members of the teams regularly provide reviews for:

- Int. Conferences and journals on Information Processing in Computer-Assisted (miccai, ipcai, media,
- Interventions, Workshop on Virtual Reality Interaction and Physical Simulation (eurographics, vriphys, ...)
- International Conference on Robotics and Automation (iros, icra,..)

10.1.1.2. Member of the Organizing Committees

Stéphane Cotin participated to the organization of the Patient-specific Computational Biomechanics Symposium at World Congress on Computational Mechanics (WCCM 2018).

10.1.2. Journal

Member of the Editorial Boards: Hadrien Courtecuisse was program chair for the international conference Eurographics 2018.

10.1.3. Invited Talks

- 2018 Stéphane Cotin: Invited lecture – workshop on “Virtual and Augmented Reality” (Toulouse, France)
- 2018 Stéphane Cotin: Invited lecture - Academy of Sciences (Paris, France)
- 2018 Stéphane Cotin: Invited lecture - BEST symposium (Strasbourg, France)

10.1.4. Scientific Expertise

Stéphane Cotin provide provides scientific expertise for the startup Insimo.

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: Yinoussa Adagolodjo, Coupling between robotics and medical simulation for automated procedures, 01/02/2016, supervised by Hadrien Courtecuisse.

PhD in progress: Jaime Garcia Guevara, Augmented ultrasound imaging for hepatic surgery, 01/09/2015, supervised by Stéphane Cotin, Marie-Odile Berger.

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

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

PhD in progress: Sergei Nikolaev, Characterization of boundary conditions for biomechanical modeling of liver, 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, 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 surgerygical interventions in deformable structures – Application to radiofrequency ablation, 01/10/2018, supervised by Hadrien Courtecuisse.

10.2.3. Juries

Hadrien Courtecuisse was a member of jury of the PhD defense of Yinoussa Adagolodjo and Fanny Morin. Strasbourg University and Grenoble University.

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