IN PARTNERSHIP WITH:
Université des sciences et technologies de Lille (Lille 1)

Activity Report 2014

Project-Team SHACRA

Simulation in Healthcare using Computer Research Advances

IN COLLABORATION WITH: Laboratoire d'informatique fondamentale de Lille (LIFL)

RESEARCH CENTER
Nancy - Grand Est

THEME
Computational Neuroscience and Medecine

Table of contents

Project-Team SHACRA

Keywords: Simulation, Image Guided Intervention, Augmented Reality, Virtual Physiology, Finite Elements, High Performance Computing

Creation of the Project-Team: 2012 January 01*, updated into Team:* 2015 January 01.

1. Members

Research Scientists
Stéphane Cotin [Team leader, Inria, Senior Researcher, HdR]
Christian Duriez [Inria, Senior Researcher, HdR]

Faculty Member
Jérémie Dequidt [Univ. Lille I, Associate Professor]

Engineers
Rémi Bessard Duparc [Inria, granted by FP7 RASIMAS project]
Eulalie Coevoet [Inria]
Marc Legendre [Inria]
Myriam Lekkal [IHU]
Bruno Marques [Inria, from Jun 2014]
Frédérick Roy [Inria]
Mario Sanz Lopez [Inria, granted by Région Nord-Pas-de-Calais]
Étienne Schmitt [Inria, from Oct 2014]
Hugo Talbot [Inria, granted by IHU Strasbourg]
Raffaella Trivisonne [IHU]

PhD Students
Vincent Majorczyk [Inria, until Mar 2014]
Alexandre Bilger [Inria, until Oct 2014]
Julien Bosman [Univ. Lille I]
François Dervaux [Univ. Lille I, until Mar 2014]
Tomas Golembiovsky [granted by Ambassade de France, until Aug 2014]
Nazim Haouchine [Inria, co-supervision with EPI MAGRIT]
Zhifan Jiang [Ecole Centrale de Lille]
Guillaume Kazmitcheff [Cifre with Collin Ltd., Inria Lille, until Feb 2014]
Frédérick Largillière [Univ. Lille I]
Mouhamadou Nassirou - Diallo [Ecole Centrale de Lille]
Christoph Paulus [Inria]
Rosalie Plantefève [Cifre with Altran, Inria Nancy]

Post-Doctoral Fellow
Huu Phuoc Bui [iCube, Univ. Lille Strasbourg]

Visiting Scientist
Laurent Thines [Clinicien, CHU Lille, Univ. Lille II]

Administrative Assistants
Véronique Constant [Inria]
Anne Rejl [Inria]

Others
Charlotte Bricout [Univ. Lille I, Internship]
Nathan Martin [Univ. Lille I, Internship]
Valentin Vergez [Inria, Internship, from May 2014 until Aug 2014]

Valerian Verona [Inria, Internship, from Mar 2014 until Aug 2014]

2. Overall Objectives

2.1. Team Overview

In recent years, an active development of novel technologies dealing with medical training has become an increasingly important area of interest in health-care manufacturing. After developing real-time simulations targeting medical training, our research group SHACRA now focuses on challenges closer to the operation room, such as pre-operative planning and intra-operative guidance. By implementing advanced physical models and realistic human-computer interaction, we achieve a higher degree of accuracy, realism and reliability of our medical simulations. Our involvement in the IHU Strasbourg through many different projects translates the close connection established with clinicians. To pursue these directions, we also assembled a team with a multidisciplinary background.

Our team leads the development of the simulation framework SOFA, on which our research work relies. Developing SOFA is the platform on which we base our research implementations. Using this single platform significantly facilitates and accelerates the development of new simulations and prototypes. Finally, our research team actively promotes its latest innovations by participating and organizing many scientific events, such as the demonstration at the Assemblée National this year or the ISBMS conference.

Figure 1. Picture of most of the members of the SHACRA team, during the ISBMS conference taking place in Strasbourg

2.2. Challenges

For more than a decade, research groups have been providing comprehensive, virtual and validated computer models of human anatomy and pathologies, mainly dedicated to medical training. The research directions of the SHACRA team essentially aim at improving the realism and fidelity of interactive simulations of medical procedures. This increase in realism makes possible to address new clinical applications, in particular per-operative guidance, that currently rely on imaging techniques, but could greatly benefit from simulation techniques. To reach these clinical objectives (without forgetting training), we have identified several key areas where important improvements remain necessary. Most of these research areas are at the intersection between several scientific domains. As illustrated in Fig. 2, they include **real-time biophysical models** (to define new models describing soft tissue deformation or physiological phenomena such as electrophysiology), **novel**

numerical strategies (to enable real-time computation even with the increase in complexity of future models), **dynamic topological representations** (to support topological changes or adaptivity of the models in areas of interest), and **image-driven simulation** (to link simulation with real world data such as the one available in an intra-operative context). The SOFA framework (http://www.sofa-framework.org) remains an essential and valuable mechanism for integrating our various contributions into a series of prototypes, facilitating validation and technology transfer.

In parallel to these scientific objectives, we also propose to focus on a number of applications, through close collaborations with clinicians. Our integration within the IHU1 in Strasbourg illustrates the relevance of our research and strengthens our clinical environment. To support these ambitious objectives, and allow us to develop prototypes that can be assessed by clinicians, we are leading a national initiative on medical simulation and on the SOFA framework with several key partners.

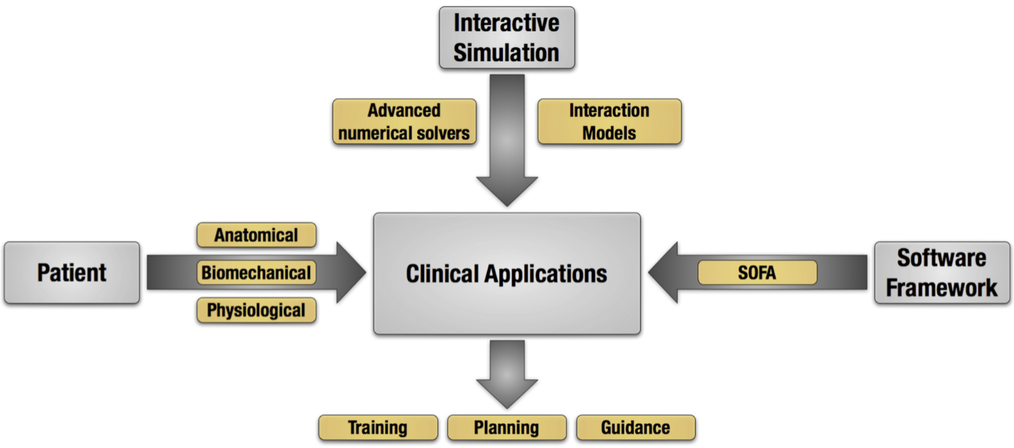


Figure 2. Overview of the team objectives (yellow boxes)

3. Research Program

3.1. Real-Time Biophysical Models

The principal objective of this scientific challenge is the modeling of the operative field, *i.e.* the anatomy and physiology of the patient that will be directly or indirectly targeted by a medical intervention. This requires to describe various phenomena such as soft-tissue deformation, fluid dynamics, electrical diffusion, or heat transfer. These models will help simulate the reaction of the patient's anatomy to the procedure, but also represent the behavior of complex organs such as the brain, the liver or the heart. A common requirement across these developments is the need for fast, possibly real-time, computation.

3.1.1. Real-time biomechanical modeling of solid structures

Soft tissue modeling holds a very important place in medical simulation. A large part of the realism of a simulation, in particular for surgery or laparoscopy simulation, relies upon the ability to describe soft tissue response during the simulated intervention. Several approaches have been proposed over the past ten years to model soft-tissue deformation in real-time (mainly for solid organs), usually based on elasticity theory and a finite element approach to solve the equations. We were among the first to propose an approach [3] using different computational strategies. Although significant improvements were obtained later on (for instance with the use of co-rotational methods to handle geometrical non-linearities) these works remain of limited clinical use as they essentially rely on linearized constitutive laws, and are rarely validated. An important part of our research remains dedicated to the development of new, more accurate models that are compatible with real-time computation. Such advanced models will not only permit to increase the realism of future training systems, but they will act as a bridge toward the development of patient-specific preoperative planning as well as augmented reality tools for the operating room.

3.1.2. Real-time biomechanical modeling of hollow structures

A large number of anatomical structures in the human body are vascularized (brain, liver, heart, kidneys, etc.) and recent interventions (such as interventional radiology procedures) rely on the vascular network as a therapeutical pathway. It is therefore essential to model the shape and deformable behavior of blood vessels. This can be done at two levels, depending of the objective. The global deformation of a vascular network can be represented using the vascular skeleton as a deformable (tree) structure, while local deformations need to be described using models of deformable surfaces. Other structures such as aneurysms, the colon or stomach can also benefit from being modeled as deformable surface, and we can rely on shell or thin plate theory to reach this objective.

3.1.3. Coupled physical models

Beyond biomechanical modeling of soft tissues, other physical phenomena have to be taken into account. In the context of percutaneous tumor ablation, both thermal and mechanical behaviors have to be modelled. Focusing especially on the simulation of cryoablation (freezing the pathological tissue), models for heat transfer have been implemented to simulate the evolution of temperature within living tissues. Pre-operative planning of the iceball can thus be envisaged. Moreover, this demonstrates the multi-physics aspect of SOFA.

3.1.4. Real-time electrophysiology

Electrophysiology plays an important role in the physiology of the human body, for instance by inducing muscles motion, and obviously through the nervous system. Also, many clinical procedures rely on electrical stimulation, such as defibrillation, neuromuscular or deep brain stimulation for instance. Yet, the modeling and the simulation of this phenomenon is still in its early stages. Our primary objective is to focus on cardiac electrophysiology, which plays a critical role in the understanding of heart mechanisms, and also in the planning of certain cardiac procedures. We propose to develop models and computational strategies aimed at real-time simulation, and to also provide personalization tools (parameter estimation) allowing to run patient-specific simulations from clinical data.

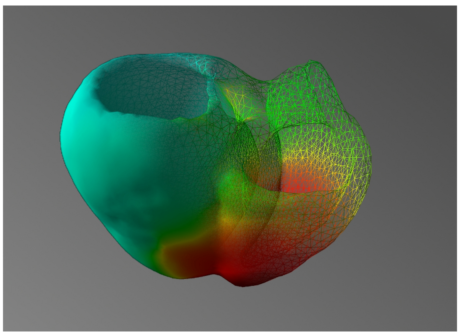


Figure 3. Patient-specific electrophysiology model of the human heart running in real-time

3.2. Numerical Methods for Complex Interactions

3.2.1. Dynamic topological changes

As mentioned previously, assisting the surgeon by providing either pre-operative planning or per-operative guidance assumes to increase the level of complexity and accuracy of our models, thus making the simulation more computationally-demanding. Innovative numerical methods must therefore be investigated. For instance, efforts are made to couple SOFA with CGoGN. CGoGN is a library based on combinatorial maps theory, specialized for representing and manipulating meshes. It is able to represent consistently objects of different dimensions composed of arbitrary cells (polygonal faces, polyhedral volumes). It provides an efficient way to explore the cells and their neighborhood; it allows to store data with the cells (both at execution time and compile time) and to efficiently modify the connectivity of the mesh even in highly dynamic cases. Adaptive meshing and efficient topological algorithm are thus available in SOFA.

3.2.2. Constraint models and boundary conditions

To simulate soft-tissue deformations accurately, the modeling technique must account for the intrinsic behavior of the modeled organ as well as for its biomechanical interactions with surrounding tissues or medical devices. While the biomechanical behavior of important organs (such as the brain or liver) has been studied extensively in the past, only few works exist dealing with the mechanical interactions between the anatomical structures. For tissue–tool interactions, most techniques rely on simple contact models, whereas advanced phenomena such as friction are rarely taken into account. While simplifications can produce plausible results in the case of interaction between the manipulator of a laparoscopic instrument and the surface of an organ, it is generally an insufficient approximation. As we move towards the simulations for planning or rehearsal, accurate modeling of contacts is playing an increasingly important role. For example, we have shown in [36] and [37] that complex interactions between a coil and an aneurysm, or alternatively between a flexible needle and a soft-tissue can be computed in real-time. In laparoscopic surgery, the main challenge is represented by modeling of interactions between anatomical structures rather than only between the instruments and the surface of the organ. Consequently, our objective was to model accurately the contacts with friction and other type on non-smooth interactions in a heterogeneous environment and to allow for stable haptic rendering. When different time integration strategies are used, another challenge is to compute the contact forces in such a way that integrity and stability of the overall simulation are maintained. Our objective was to propose a unified definition of such various boundary conditions and develop new numerical methods for simulations of heterogeneous objects.

3.3. Image-Driven Simulation: towards pre-operative planning and per-operative guidance

Image-guided therapy is a recent area of research that has the potential to bridge the gap between medical imaging and clinical routine by adapting pre-operative data to the time of the procedure. Several challenges are typically related to image-guided therapy, such as multi-modality image registration, which serves to align pre-operative images onto the patient. As most procedures deal with soft-tissues, elastic registration techniques are necessary to perform this step. Novel registration techniques began to account for soft tissue deformation using physically-based methods. Yet, several limitations still hinder the use of image-guided therapy in clinical routine. First, as registration methods become more complex, their computation time increases, thus lacking responsiveness. Second, as we have seen previously, many factors influence the deformation of soft-tissues, from patient-specific material properties to boundary conditions with surrounding anatomy. Another very similar, and related, problem is augmented reality, i.e. the real-time superposition of a virtual model onto the reality. In a clinical context, this can be very useful to help "see through" the anatomy. In this case, however, real-time registration of the virtual information onto the patient is mandatory. Our objective in this area is to combine our expertise in real-time soft-tissue modeling, complex interactions with image data to provide accurate and real-time registration, deformation, and tracking of virtual anatomical structures onto the patient.

The predictive capabilities of computer simulations may also be used to improve minimally invasive surgical procedures. While simulation results are sensitive to model parameters, initial and boundary conditions, we aim at combining computer-vision algorithms and simulation algorithms in order to produce dynamic data-driven simulation in clinical applications. The main idea is to use computer-vision algorithms from pre-operative diagnoses or per-operative video streams in order to extract meaningful data to feed the simulation engine and thus to increase the accuracy of the simulation. Clinical outcomes are expected in interventional radiology where the guidance is based on fluoroscopic imaging modality inducing high absorbed dose of X-rays for the patient and the clinical staff. In that context, using the prediction capabilities of the simulation may decrease the acquisition frequency of images, leading to a lower exposure of X-rays. Our objective in this area is to combine our expertise in patient-specific modeling and constraint models to achieve the dynamic coupling between images, pre-operative data and computer simulation.

4. New Software and Platforms

4.1. SOFA

4.1.1. Description of the SOFA framework

SOFA [1] is an open-source software framework targeted at real-time multi-physics simulation, with an emphasis on medical simulation. The idea of SOFA was initiated by members of the SHACRA team, strongly supported by Inria and still actively developed within the SHACRA team. Based on C++, the SOFA engine provides many algorithms, physiological models and anatomical data, made available within a plugin architecture. With its high level of modularity, SOFA appears to be an efficient tools to benchmark and develop new medical technologies using existing algorithms.

The SOFA framework relies on a multi-model representation which allows to have several representations (e.g. mechanical, thermal and visual) of the same object. Those different representations are connected together through a mechanism called mapping. With this features, it is also possible to have models of very different nature interacting together, for instance rigid bodies, deformable objects, and fluids. CPU and GPU implementations can be transparently combined to exploit the computational power of modern hardware architectures.

SOFA is at the heart of a number of research projects, including cardiac electro-physiology modeling, interventional radiology planning and guidance, planning for cryosurgery and deep brain stimulation, robotics, percutaneous procedures, laparoscopic surgery, non-rigid registration, etc. As proof of its success, SOFA has been downloaded nearly 150,000 times, and is used today by many research groups around the world, as well as a number of companies. The mailing list used to exchange with the community includes several hundreds of researchers, from about 50 different institutions. SOFA is currently used by a number of companies (Siemens Corporate Research, Digital Trainers, Epona Medical, Moog, SenseGraphics, etc.) and also provides the key technology on which our newly created start-up (InSimo) is relying. We strongly believe that today SOFA has become a reference for academic research, and is increasingly gaining recognition for product prototyping and development. The best illustration of this worldwide positioning is the role of SOFA in the challenge set by the HelpMeSee foundation to win the contract for the development of a very ambitious and high-risk project on cataract surgery simulation.

4.1.2. Consortium

At the end of the year 2014, the creation of a consortium SOFA has been enacted. The purpose of this consortium is to define the suitable orientation in terms of development, lead to its achievement while creating a propitious ecosystem for research, industry and for the creation of numerous startups. Beside lead the development of SOFA, this consortium has to maintain the existing code, and last but not least, manage the SOFA community and help it to grow.

[1] More information about SOFA at http://www.sofa-framework.org

4.1.3. SOFA Day after ISBMS'14

On the occasion of the 6th ISBMS conference, we organized a "SOFA Day" giving us a unique opportunity to meet SOFA users from various research institutes or companies, and exchange about the future improvements and development of the engine. We use these occasions to share and discuss with SOFA users, to refine the roadmap and stay tuned with our audience.

4.1.4. A new website

Finally, a new website has been developed during the last month of the year. The final version of the website will be released in spring 2015. The website is a very important tool for the community (especially new users). The SOFA consortium will be in charge of this assignment.

5. New Results

5.1. Highlights of the Year

5.1.1. Intra-operative guidance

Each year in Europe 50,000 new liver cancer cases are diagnosed for which hepatic surgery combined to chemotherapy is the most common treatment. In particular the number of laparoscopic liver surgeries has increased significantly over the past years. Minimally invasive procedures are challenging for the surgeons due to the limited field of view.

Providing new solutions to assist surgeons during the procedure is of primary interest. This year, the team developed an innovative system for augmented reality in the scope of minimally invasive hepatic surgery. The first issue is to align preoperative data with the intra-operative images. We first proposed a semi-automatic approach [28] for solving the ill-posed problem of initial alignment for augmented reality systems during liver surgery. Our registration method relies on anatomical landmarks extracted from both the laparoscopic images and a three-dimensional model, using an image-based soft-tissue reconstruction technique and an atlas-based approach, respectively.

Second, we introduced a method for tracking the internal structures of the liver during robot-assisted procedures [25]. Vascular network, tumors and cut planes, computed from pre-operative data, can be overlaid onto the laparoscopic view for image-guidance, even in the case of large motion or deformation of the organ. This is made possible by relying on a fast yet accurate 3D biomechanical model of the liver combined with a robust visual tracking approach designed to properly constrain the model. Our augmented reality proved to be accurate and extremely promising on in-vivo sequences of a human liver during robotic surgery.

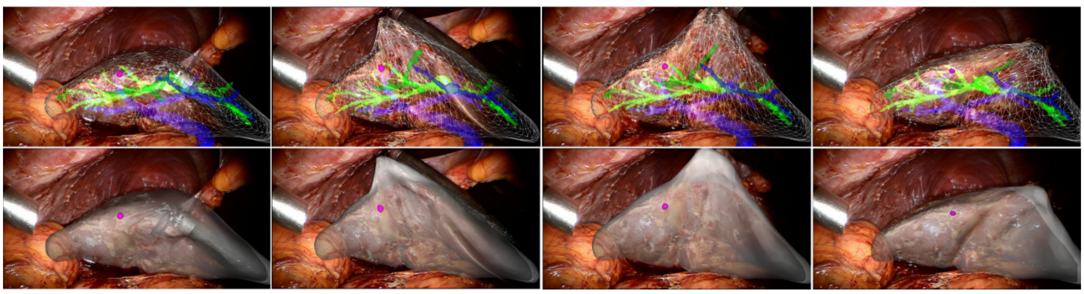


Figure 4. Augmented reality on the liver with 3D visualization of the blood vessels

5.1.2. Ph.D. defenses

The year 2014 was also special since many PhDs have been defended. Four PhD defenses took place with:

- Ahmed Yureidini's defense about *Robust blood vessel surface reconstruction for interactive simulations from patient data* [15] in May 2014,
- Guillaume Kazmitcheff's defense about *Minimal invasive robotics dedicated to otological surgery* [13] in June 2014,
- Hugo Talbot's defense about *Interactive patient-specific simulation of cardiac electrophysiology* [14] in July 2014,
- Alexandre Bilger's defense about *Patient-specific biomechanical simulation for deep brain stimulation* [12] in December 2014.

5.1.3. Organization of ISBMS 2014

The team co-organized the 6^{th} International Symposium on Biomedical Simulation (ISBMS) 2014, which was held in Strasbourg (France) on October 16 – 17, 2014. The ISBMS conference is a well-established scientific meeting that provides an international forum for researchers interested in using biomedical simulation technology for the improvement of patient care and patient safety. The SiMMS group from Imperial College London and IHU-Strasbourg were the two other co-organizers. The event was hosted at IRCAD, a center of excellence in surgical training. The ISBMS chairs were:

- Stéphane Cotin (Inria),
- Fernando Bello (Imperial College London),
- Jérémie Dequidt (Univ. Lille),
- Igor Peterlik (IHU Strasbourg & Masaryk Univ.).

The whole team was involved in the organization of the event. About 65 participants joined the conference. Regarding their feedback, the conference was a real success. For more information about ISBMS, refer to the official website http://www.isbms.org.

Finally, a day dedicated to our software SOFA ("SOFA Day") was organized the day after the ISBMS conference. This was the opportunity to introduce SOFA to the ISBMS community and to share with the SOFA users.

(a) Setup of our demo (b) With Genevieve Fioraso

Figure 5. Presentation of our work at the French National Assembly. Genevieve Fioraso is the French national research secretary

5.1.4. Demonstration at the French National Assembly

On Tuesday 21st January 2014, the team SHACRA presented its work during the "Internet et société numérique" working group. This was a joint event between Inria and the French National Assembly (Assemblée Nationale). On this special occasion, we made a demonstration of our simulations and the CEO from Inria Michel Cosnard also presented more globally the role of Inria in healthcare but also education, cloud computing, big data.

5.2. New Results

5.2.1. Real-Time Biophysical Models

5.2.1.1. Deep brain stimulation

Participant: Alexandre Bilger.

During this year, we developed an intra-operative registration method. It is used during a DBS surgery and can help the surgeon to locate anatomical structures for a safer and a more efficient treatment [21]. The method is based on the biomechanical model of brain shift we developed during the last years. Because some parameters of the model are unknown, we propose to estimate them with an optimization process. The cost function evaluates the distance between the model and the segmentation of pneumocephalus, the only indicator of brain shift visible on an intra-operative CT scan.

Figure 6. Biomechanical model of the brain for DBS planning

5.2.1.2. Stapedectomy

Participant: Guillaume Kazmitcheff.

Stapedectomy is a challenging procedure of the middle ear microsurgery, since the surgeon is in direct contact with sensitive structures such as the ossicular chain. This procedures is taught and performed in the last phase of the surgical apprenticeship. To improve surgical teaching, we propose to use a virtual surgical simulator [26] based on a finite element model of the middle ear. The static and dynamic behavior of the developed finite element model was successfully compared to published data on human temporal bones specimens. A semi-automatic algorithm was developed to perform a quick and accurate registration of our validated mechanical atlas to match the patient dataset. This method avoids a time-consuming work of manual segmentation, parameterization, and evaluation. A registration is obtained in less than 260 seconds with an accuracy close to a manual process and within the imagery resolution. The computation algorithms, allowing carving, deformation of soft and hard tissus, and collision response, are compatible with a real-time interactive simulation of a middle ear procedure. As a future work, we propose to investigate new robotized procedures of the middle ear surgery in order to develop new applications for the RobOtol device and to provide a training tool for the surgeons.

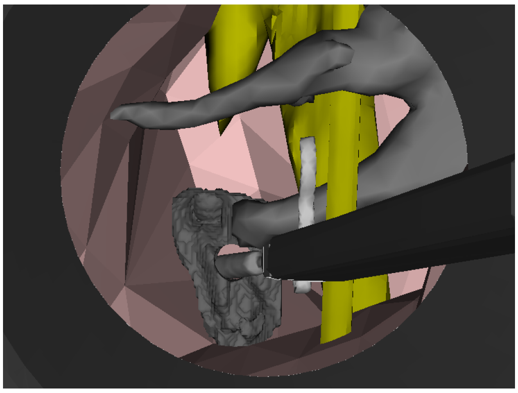


Figure 7. Simulation of the stapedotomy procedure

5.2.1.3. Cardiac electrophysiology

Participant: Hugo Talbot.

Cardiac arrhythmia is a very frequent pathology that comes from an abnormal electrical activity in the myocardium. The skills required for such interventions are still very challenging to learn, and typically acquired over several years. We first developed a training simulator for interventional electrocardiology and thermo-ablation of these arrhythmias [14], [32]. Based on physical models, this training system reproduces the different steps of the procedure, including endovascular navigation, electrophysiological mapping, pacing and cardiac ablation. Based on a scenario of cardiac arrhythmia, cardiologists assessed the interactivity and the realism of our simulation.

Figure 8. Training simulator for electrocardiology procedures

Beyond electrophysiology training, our work around the cardiac electrophysiology also target the personalization of our mathematical models. Using the dense electrograms recorded intra-operatively, we presented an accurate and innovative approach to personalize our model, i.e. estimate patient-specific parameters. The modeling in silico of a patient electrophysiology is needed to better understand the mechanism of cardiac arrhythmia. This work has been submitted in a conference.

5.2.1.4. Cryoablation

Participant: Hugo Talbot.

A new project started this year around cryotherapy. This technique consists in inserting needles that freezing the surrounding tissues, thus immediately leading to cellular death of the tissues. Cryoablation procedure is used in many medical fields for tumor ablation, and even starts being used in cardiology. In this scope, we build a simulator able to place the cryoprobes and run a simulation representing the evolution of iceballs in living tissues [31]. This work was presented at MMVR'14.

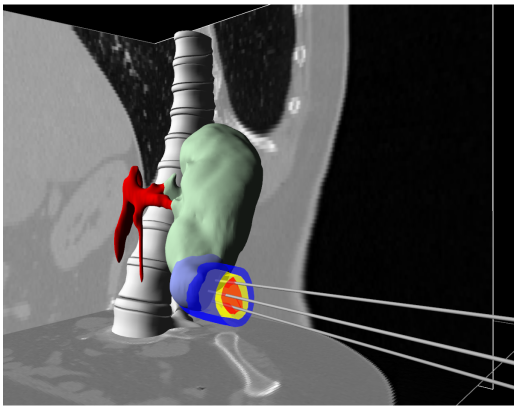


Figure 9. Simulation of the stapedotomy procedure

5.2.1.5. Connective tissues

Participant: Julien Bosman.

Another topic of simulation is the modeling of connective tissues [18]. First, a comparative study on the influence of the ligaments in liver surgery has been conducted. This study underlines that the model chosen for the ligament's has a strong influence on the outcome of the simulation. More specifically, it shows the the model is at least as much important as the material parameters of the parenchyma. It also shows that the influence of the model depends on the type of effort that is prescribed on the liver. The second axis concerns the validation of a frame (6-DOF nodes) based mechanical model developed for ligaments simulation. Current results show that this model requires less degrees of freedom while providing the same accuracy as a traditional FEM model. At last, a method dedicated to the simulation and the control of continuum robots has been developed. The goal of this method is to replace the mesh of robot by computing its compliance and applying it on a reduced model made of frames. It allows to strongly decrease the number of degrees of freedom needed for the robot simulation while keeping the needed accuracy.

5.2.1.6. Simulation of lipofilling reconstructive surgery

Participant: Vincent Majorczyk.

We have developed a method to simulate the outcome of reconstructive facial surgery based on fat-filling. Facial anatomy is complex: the fat is constrained between layers of tissues which behave as walls along the face; in addition, connective tissues that are present between these different layers also influence the fat-filling procedure. To simulate the end result, we have proposed a method which couples a 2.5D Eulerian fluid model for the fat and a finite element model for the soft tissues. The two models are coupled using the computation of the mechanical compliance matrix. We had two contributions: a solver for fluids which couples properties of solid tissues and fluid pressure, and an application of this solver to fat-filling surgery procedure simulation.

5.2.1.7. Inverse FEM simulation

Participant: Eulalie Coevoet.

We introduced a new methodology for semi-automatic deformable registration of anatomical structures [23], using interactive inverse simulations. We applied the approach for the registration of the parotid glands during the radiotherapy of the head and neck cancer. Radiotherapy treatment induces weight loss that modifies the shape and the positions of these structures and they eventually intersects the target volume. We proposed a method to adapt the planning to limit the radiation of these glands.

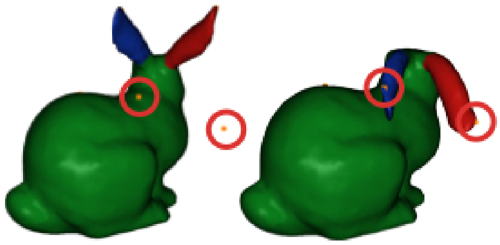


Figure 10. Numerical validation. Left: Target points (highlighted in red) after setting 3 different Young's moduli (one color by Young's modulus). Right: The resulting deformation once the Young modulus have been estimated.

5.2.2. Numerical Methods for Complex Interactions

5.2.2.1. Cliping in neurosurgery

Participant: Eulalie Coevoet.

We developed a simulator for neurosurgery. The surgery consist in "clipping" a cerebral aneurysm. Aneurysm is an abnormal local dilatation in the wall of a blood vessel, usually an artery. There are several treatment options for people with the diagnosis of cerebral aneurysm. Medical therapy, surgical therapy (clipping) and endovascular therapy (coiling). The surgical therapy, because of his invasive and technical nature, is the less prescribed. This leads to less and less surgeon trained to practice the procedure. And yet some patients require the surgical way. So the idea was to develop a simulator to train student and also help on the planification.

5.2.2.2. Virtual cutting

Participants: Huu Phuoc Bui, Christoph Paulus.

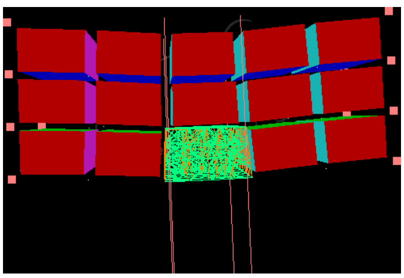


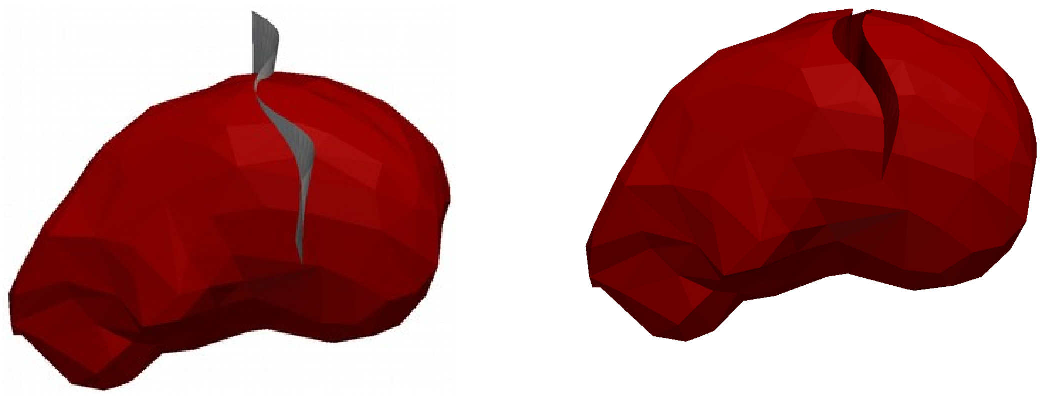
Figure 11. Cutting simulation using LEM

The simulation of cutting is a central interest in the team. Several approaches have been investigated this year to model surgical cuts, tearing and other separations of materials induced by surgical tools:

- using the standard finite element method (FEM) combined with a re-meshing approach, that replaces locally the current structure of the mesh in order to allow for a separation,
- using the extended FEM (X-FEM) that uses shape functions that can model discontinuities inside elements (see Fig. 12),
- and using the Lattice element method (LEM).

A re-meshing approach to model cuts has been submitted to several conferences, we are waiting for the response. An implementation of the extended finite element method was published in a preprint "Simulation of Complex Cuts in Soft Tissue with the Extended Finite Element Method (X-FEM)". The figures below show a simulation of a sinusoidal cut on a liver executed with the implementation of the X-FEM.

For the LEM approach (see Fig. 11), a multimapping between finite elements and lattice model have been developed and implemented into SOFA framework. This allows us to perform a multiscale simulation in real-time. A dynamic changing of topology between finite elements and lattices should be developed in the next step in order to perform the cutting dynamically.



(a) Plane of cut (b) Result of the cutting

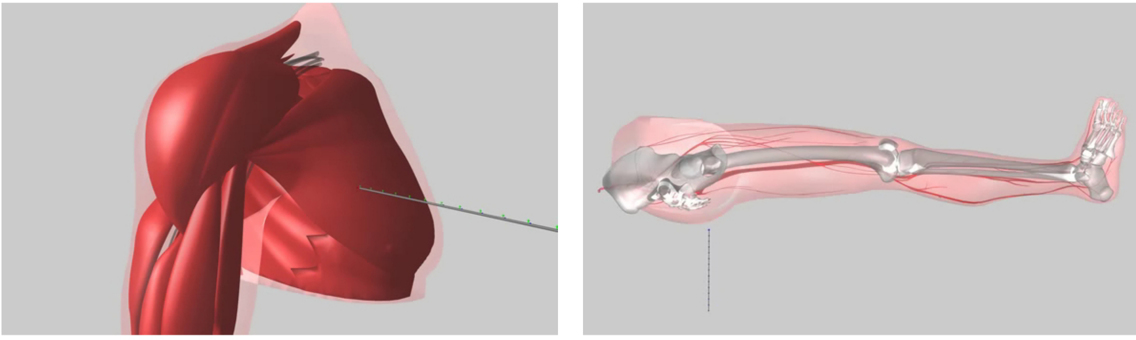
Figure 12. Cutting simulation based on X-FEM

5.2.2.3. Regional anaesthesia

Participants: Rémi Bessard Duparc, Frédérick Roy.

The RASimAs project (Regional Anaesthesia Simulator and Assistant) is a European research project funded by the European Union’s 7th Framework Program. It aims at providing a virtual reality simulator and assistant to doctors performing regional anaesthesia by developing the patient-specific Virtual Physiological Human models. This year, the code for needle insertion has been re-designed and simplified into SOFA and the muscle contraction has been implemented. Finally, the components of the simulation have been optimized to reach the desired real-time performances (i.e more than 25-30 frames per second).

Our preliminary results are awaiting the validation of the Working Packages in January 2015. The needle refactoring will be shared with an other project in Strasbourg (robot) and may be shared with an other team at Inria Rennes with the LAGADIC Team.



(a) Needle insertion in the shoulder (b) Needle insertion in the leg

Figure 13. Regional anaesthesia with needle insertion and muscle contraction

5.2.2.4. Control of elastic soft robots

Participant: Frédérick Largillière.

We developed a prototype of stiffness-controlled haptic interface using a piece of silicone rubber to render different forces related to a displacement ie. different stiffnesses and an improved method of simulation using multi-rate loops to try to keep the computation real-time even with models using a large number of FEM elements. (work currently under review) We also presented the idea of a surgical robot able to virtually reconstruct its environment (ie. surrounding biological tissues) through small modifications of the algorithm used for controlling soft robots (SURGETICA 2014).

5.2.3. Image-Driven Simulation

5.2.3.1. Physics-based registration algorithms

Participant: Rosalie Plantefève.

Before targeting the augmented reality for laparoscopic operations, an important step consists in solving the initial alignment problem. Given a pre-operative image of the organ (usually a CT scan) a detailed mesh is constructed. To make the information stored in this mesh available during the operation, the mesh must be registered onto the intra operative view. However, mainly due to the pneumoperitoneum, the organ has undergone important deformation between the pre-operative images acquisition and the operation. The pre-operative shape and the intra-operative shape of the organ do not correspond. Therefore a non rigid registration is required to align the mesh and the real organ. Our registration algorithms also allowed us to work on a mean to automatically recover boundary conditions of a patient specific liver.

We created a statistical atlas [29] of the human liver to store some of the liver boundary conditions positions : the veina cava and the anchor point of the falciform ligament positions. This method was presented at MICCAI 2014. We also developed a new registration method [28] that evolves automatically from a rigid registration to a non rigid registration to solve the initial alignment problem. The method use some anatomical features of the liver such as the anchor point position of the falciform ligament. This method was presented at ISBMS 2014.

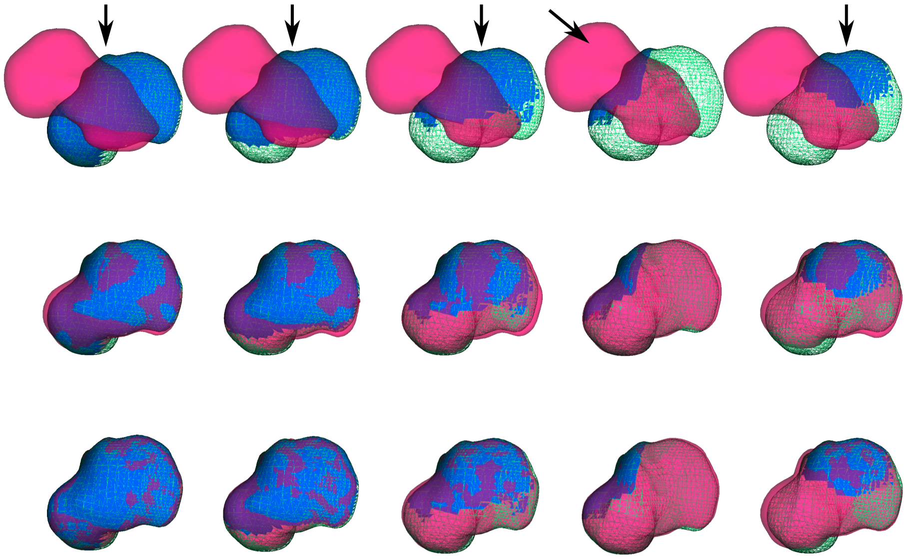


Figure 14. Results showing the initial alignment of a liver between pre-operative and intra-operative data

5.2.3.2. Augmented reality

Participant: Nazim Haouchine.

After this intra-operative registration, the augmented reality is possible. This topic is one the highlight of the year 2014. In 2014, we proposed a method for real-time augmented reality of internal liver structures during minimally invasive hepatic surgery [25]. This project is done is collaboration with the EPI MAGRIT. Vessels and tumors computed from pre-operative CT scans can be overlaid onto the laparoscopic view for surgery guidance. Compared to current methods, our method is able to locate the in-depth positions of the tumors based on partial three-dimensional liver tissue motion using a real-time biomechanical model. This model permits to properly handle the motion of internal structures even in the case of anisotropic or heterogeneous tissues, as it is the case for the liver and many anatomical structures. Experimentations conducted on phantom liver permits to measure the accuracy of the augmentation while real-time augmentation on in vivo human liver during real surgery shows the benefits of such an approach for minimally invasive surgery. Finally, a method for 3D reconstruction of elastic shapes with self-occlusion handling was also proposed.

5.2.3.3. Segmentation

Participant: Zhifan Jiang.

We have been working on medical image analysis in the context of the female pelvic medicine. Image-based diagnoses of pelvic floor disorders like prolapse or endometriosis rely on mechanical indicators, such as mobilities of organs and shear displacements between organs. Image data do not provide directly qualitative indicators hence analysis and diagnosis of medical are required although unfortunately subjected to surgeon expertise subjectivity. Therefore, objective information would be useful for both precise diagnoses and planning of surgical procedure. The objective is to develop numerical tools which extract quantitative information from static and cine MR images based on algorithms of detection and tracking.

We have developed numerical models not only for visualization, but also for quantitative measurements on a group of organs, such as their shapes and their relative movements. The numerical tool extracts these quantitative information (displacements and shear inter-organ) as well as the geometric shape of organs from images via Model-to-Image registration based on B-spline models. Our approach enables to identify multiple

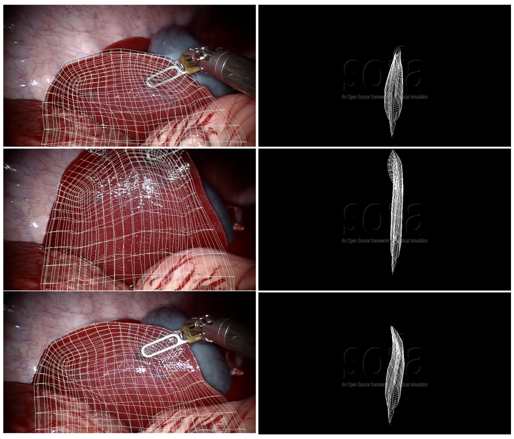


Figure 15. Augmented reality view of a liver during laparoscopic surgery

organ shapes in a single 2-dimension MR image and then to track their motion in a sequence of 2-dimension dynamic (cine) MR images for the study of the mobilities of the pelvic system. The method has been tested on healthy and pathological patient-specific data (19 patients) and the results provide valuable data to assess the shear displacement between organs and therefore making it possible to identify weakened ligaments or fascia which function differently in patients having pathologies. However, the results are to be validated by further mechanical FEM simulations. This work has been accepted in the journal STRAIN.

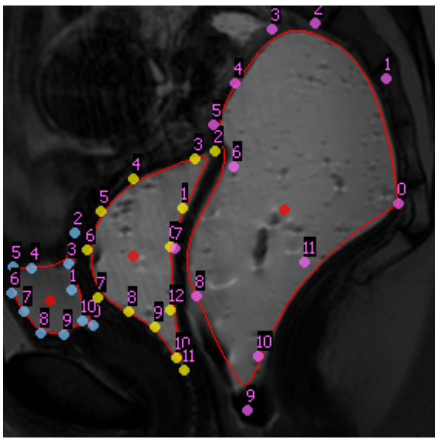


Figure 16. Contour segmentation on the pelvic system

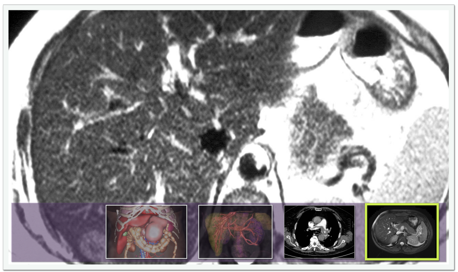
5.2.3.4. MIND project

Participants: Myriam Lekkal, Raffaella Trivisonne.

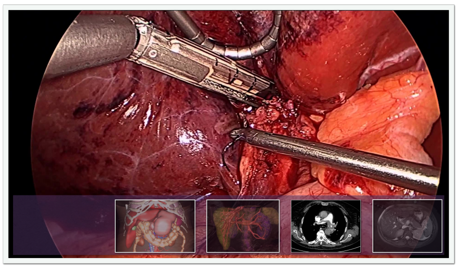
Within a feasibility study contest, we worked on Human Computer Interaction developing a new, intuitive and efficient way to interact with medical information in modern operating room. Nowadays operating rooms are progressively outfitted with computerized equipment necessary to access and manipulate a significant amount of data (i.e. medical images, patient's records, patient's vitals and physical parameters of the operating environment). This type of equipment belongs to the non-sterile section of an operating room, therefore surgeons, who are not allowed to be contaminated, cannot directly interact with it.

The idea of MIND project is to create a new device that could be used alone, such as a remote control, or easily integrated onto several locations, according to user preferences or constraints from the surgical procedure. Through this remote control, surgeons are able to access and manipulate medical information within the operating field and without leaving the instruments. For the software side the main aspects are distributed in two categories: a low level library, in charge of tasks such like handling the communications between the wireless instrument and the central computer, and a set of high-level functionalities and applications concerning the development of users GUI and new applications according to the needs of the case.

This work resulted in a patent [35] (still pending). Read more here http://mindsurgeonmouse.weebly.com/.



(a) View 1



(b) View 2

Figure 17. Example of the MIND GUI

6. Bilateral Contracts and Grants with Industry

6.1. Bilateral Contracts with Industry

InSimo is a startup we created in January 2013, after two years of thinking, maturation and incubation. Its founding members are all former or actual team members of SHACRA: Jeremie Allard, Juan Pablo de la Plata Alcalde and Pierre Jean Bensoussan have joined the operation team, while Stéphane Cotin and Christian Duriez serve as scientific advisors. The business model of the company is based on the SOFA platform and its community to transfer state-of-the-art simulation technologies into commercially-supported software components that medical simulator vendors can integrate into their products. The goal is to foster the creation of a new generation of medical simulators, highly realistic, faster to develop, allowing a broader commercial offer and novel uses. InSimo participated to the 2012 OSEO / MESR national innovative technology company creation competition (Emergence category) and was selected as the best project in the Alsace region as well as one of the three projects highlighted at the national level. InSimo also won the HelpMeSee contract (in partnership with Moog and SenseGraphics) and entered in February 2013 into a 3-year development phase to build a first batch of 100 MSICS simulators.

6.2. Bilateral Grants with Industry

The collaboration is set with INSERM - UMR-S 867 (minimal invasive and robotized otological surgery) Faculté de Médecine Paris Diderot Paris 7 and with the company Collin SA (Bagneux, France) which is developing some activities in the domain of the head and neck (surgical robot such as RobOtol, middle ear implants, surgical instruments, surgical navigation, ...). The objective of this project is to obtain a simulation tool applied to the ear surgery for both training and planning of conventional and robotized middle ear surgery. In addition, the aim of this work is to provide a tool able to explore, develop and assess new robotized procedures using a tele-operated device called RobOtol. Guillaume Kazmitcheff is doing his PhD in the context of this collaboration: he is paid by a CIFRE contract with Collin, he is mainly working with the INSERM team but the design of the simulation is done in collaboration with our group and he is enrolled in the university of Lille 1.

7. Partnerships and Cooperations

7.1. National Collaborations

The team is collaborating with many national partners, such as:

- the Oscar Lambret Hospital in the context of the interactive inverse FEM simulation (Luis Shiapacasse, Nick Reynaert and Eric Lartigau),
- CHR Lille (Laurent Thines),
- the radiology department of Nancy Hospital within the IDeaS project,
- the TeamC research lab,
- the Inria ASCLEPIOS research team,
- the Inria EVASION research team,
- the Inria MARGRIT research team,
- the Inria LAGADIC research team.

7.2. National Initiatives

7.2.1. Sofa, OR

In December 2014, a new ADT national initiative started. The objective of this ADT is twofold: first, we aim at achieving a level of quality and robustness compatible with IEC 62304 for the core of SOFA and a reduced set of components. This does not include the certification of the code itself, but rather the implementation of a comprehensive development process that will enable the certification by companies wishing to integrate this code into their systems. The second objective is to add new features specific to the needs of using intra-operative: interoperability with equipment from the operating room, acquisition and real-time processing of full HD video streams, data assimilation and predictive filters, path planning, visualization for augmented reality, or user interfaces dedicated to the operating room.

7.2.2. RESET

At the end of the year, the team has been awarded a new ANR project: RESET. This project will start in March 2015. Its objective is to develop a high-fidelity training system for retinal surgery. Retina surgery is an increasingly performed procedure for the treatment of a wide spectrum of retinal pathologies. Yet, as most micro-surgical techniques, it requires long training periods before being mastered. This simulator will be built upon our strong scientific expertise in the field of real-time simulation, and our success story for technology transfer in the field of cataract surgery simulation (MSICS simulation developed for the HelpMeSee foundation).

7.2.3. Sofa, ADT

SOFA Large Scale Development Initiative (ADT) : the SOFA project (Simulation Open Framework Architecture) is an international, multi-institution, collaborative initiative, aimed at developing a flexible and open source framework for interactive simulations. This will eventually establish new grounds for a widely usable standard system for long-term research and product prototyping, ultimately shared by academic and industrial sites. The SOFA project involves 3 Inria teams, SHACRA, IMAGINE and ASCLEPIOS. The development program of the ADT started in 2007.

7.2.4. ANR Acoustic

The main objective of this project is to develop an innovative strategy based on models for helping decision-making process during surgical planning in Deep Brain Stimulation. Models will rely on different levels involved in the decision-making process; namely multimodal images, information, and knowledge. Two types of models will be made available to the surgeon: patient specific models and generic models. The project will develop methods for 1) building these models and 2) automatically computing optimal electrodes trajectories from these models taking into account possible simulated deformations occurring during surgery. The project belongs to the multidisciplinary domain of computer-assisted surgery (CAS). Computer assisted surgery aims at helping the surgeon with methods, tools, data, and information all along the surgical workflow. More specifically, the project addresses surgical planning and surgical simulation in Image Guided Surgery. It is related to the exponentially growing surgical treatment of Deep Brain Stimulation (DBS), originally developed in France by Pr. Benabid (Grenoble Hospital). The key challenges for this research project are 1) to identify, extract, gather, and make available the information and knowledge required by the surgeon for targeting deep brain structures for stimulation and 2) to realistically simulate the possible trajectories.

7.2.5. IHU, Strasbourg

Our team has been selected to be part of the IHU of Strasbourg. This new institute, for which funding (67M€) has just been announced, is a very strong innovative project of research dedicated to future surgery of the abdomen. It will be dedicated to minimally invasive therapies, guided by image and simulation. Based on interdisciplinary expertise of academic partners and strong industry partnerships, the IHU aims at involving several specialized groups for doing research and developments towards hybrid surgery (gesture of the surgeon and simulation-based guidance). Our group and SOFA have a important place in the project. Since September 2011 a part of our team is located within the IHU, to develop a number of activities in close collaboration with clinicians.

7.2.6. ANR IDeaS

IDeaS is a project targeted at per-operative guidance for interventional radiology procedures. Our main goal is to provide effective solutions for the two main drawbacks of interventional radiology procedures, namely: reduce radiation exposure and provide a fully 3D and interactive visual feedback during the procedure. To do so, our project relies on an original combination of computer vision algorithms and interactive physics-based medical simulation. Computer vision algorithms extract relevant information (like the actual projected shape of the guide-wire at any given time) from X-ray images, allowing adjusting the simulation to real data. Conversely, computer-based simulation is used as a sophisticated and trustful predictor for an improved initialization of computer vision tracking algorithms. Many outcomes may be expected both in scientific and clinical aspects. On the scientific side, we believe a better understanding of how real data and simulation should be merged and confronted must lead, as a natural by-product, to image-based figures of merit to actually validate computer-based simulation outputs against real and dynamic data. A more accurate identification of the factors limiting the realism of simulation should follow with a rebound impact on the quality of the simulation itself. An actual integration of a mechanical model into the loop will improve the tracking. We firmly believe mechanical constraints can supplement the image data such that dynamic single view reconstruction of the interventional devices will be possible. On the clinical side, using the prediction capabilities of the simulation may decrease the need for X-ray images at high rates, thus leading to lower exposure to radiations for the patients and surgical staff. Finally, the output of the simulation is the 3D shape of the tool (e.g. guide-wire or catheter), but not only. Additional information may be visualized, for instance pressure of the catheter on the arterial wall, to prevent vessel wall perforations, or reduce stress on the arterial wall to prevent spasm. More generally, richer information on the live procedure may help surgeons to reduce malpractice or medical errors.

7.3. European Initiatives

7.3.1. RASimAs

2014 was the first year of the RASimAs project (STREP project funded under FP7) during which we developed new models of the biomechanics of the leg and arm, as well as the simulation of the insertion of the anaesthesiology needle. Regional anaesthesia has been used increasingly during the past four decades. This is addressed to the perceived advantages of reduced postoperative pain, earlier mobility, shorter hospital stay, and significantly lower costs. Current training methods for teaching regional anaesthesia include cadavers, video teaching, ultrasound guidance, and simple virtual patient modeling. These techniques have limited capabilities and do not consider individual anatomy. The goal of this project is to increase the application, the effectiveness and the success rates of RA and furthermore the diffusion of the method through the development VPH models for anaesthesia. The goal of the SHACRA team is to provide the computational infrastructure for the physics-based simulation and to propose new methods for patient-specific modeling and simulation of soft tissues and their interaction with the needle, including its effect on nerve physiology.

See http://rasimas.imib.rwth-aachen.de for more details.

7.4. International Initiatives

7.4.1. Informal International Partners

The team is collaborating with:

- the King's College of London,
- Aachen University (Germany),
- Bangor University (United Kingdom),
- Universidad Rey Juan Carlos (Spain),
- Foundation for Research and Technology Hellas (Greece),
- SenseGraphics (Sweden).

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. ISBMS 2014

The 6th International Symposium on Biomedical Simulation 2014 (for detailed information, http://www.isbms.org) took place in Strasbourg on the $16 - 17^{th}$ October. Stéphane Cotin and all the team in Strasbourg organized the conference with help from the IHU Strasbourg. The conference was followed by a "SOFA Day". This event was a real success: 65 persons attended the conference and participants gave very positive feedback for both ISBMS conference and "SOFA Day".

8.1.2. Scientific events organisation

8.1.2.1. General chair, scientific chair

- Stéphane Cotin was member of the HCERES (Haut Conseil de l'évaluation de la recherche et de l'enseignement supérieur).

8.1.3. Scientific events selection

8.1.3.1. Chair of conference program committee

Stéphane Cotin was chair of ISBMS 2014 (6th International Symposium on Biomedical Simulation).

8.1.3.2. Member of the conference program committee

- Stéphane Cotin was:
  - members of the organizing committee of the 6^{th} ISBMS conference,
  - member of the organizing committee of the 2^{nd} workshop MICCAI DBSMC (Deep Brain Stimulation Methodological Challenges),
  - scientific member of the 3^{rd} Workshop Francophone M-DBS (Modèles en Stimulation Cérébrale Profonde) - Planning, Implantation et Evaluation Post-opératoire.
- Christian Duriez was co-chair of:
  - EuroHaptics 2014 in Paris,
  - VRIPHYS 2014.
- Jeremie Dequidt was PC member of:
  - AFIG'2014,
  - ISBMS 2014.
- Alexandre Bilger was member of the organizing committee of the 2^{nd} workshop MICCAI DBSMC (Deep Brain Stimulation Methodological Challenges),
- All members of the team SHACRA were involved in the organization of the ISBMS conference.

8.1.3.3. Reviewer

- Stéphane Cotin has been reviewer for:
  - MICCAI,
  - IPCAI.
- Christian Duriez has been reviewer for:
  - EuroHaptics 2014,
  - VRIPHYS 2014,
  - IROS 2014,
  - ICRA 2014,
  - ISBMS 2014,
  - SIGGRAPH ASIA 2014.
- Jeremie Dequidt has been reviewer for:
  - EuroHaptics 2014,
  - VRIPHYS 2014,
  - MICCAI 2014.

8.1.4. Journal

8.1.4.1. Member of the editorial board

- Stéphane Cotin was:
  - editor of the proceeding of the 6th International Symposium, ISBMS 2014, Strasbourg, France, October 16-17, 2014, Lecture Notes in Computer Science, Vol. 8789 (Theoretical Computer Science and General Issues) - Bello, Fernando, Cotin, Stéphane (Eds.),
  - editor for Information processing in computer-assisted interventions, IJCARS. 2014; 9(5): 755–757 (Dean Barratt,corresponding author Pierre Jannin, Gabor Fichtinger, and Stephane Cotin).
- Christian Duriez was editor of the proceedings EuroHaptics 2014.

8.1.4.2. Reviewer

- Stéphane Cotin has been reviewer for:
  - Media,
  - and IJCARS.
- Christian Duriez has been reviewer for:
  - the international journal CVIU (Computer Vision and Image Understanding),
  - IEEE Transaction on Haptics (3 papers),
  - ACM Transaction on Medical Imaging,
  - The Visual Computer Journal.
- Jeremie Dequidt has been reviewer for:
  - the French journal REFIG,
  - he international journal CMPB (Computer Methods and Programs in Biomedicine),
  - ACM Transaction on Medical Imaging,
  - the international journal MedIA (Medical Image Analysis)
- Hugo Talbot has been reviewer for the IBBWIO journal.

8.2. Teaching - Supervision - Juries - Invited Talks - Events

8.2.1. Teaching

- Christian Duriez teached:
  - FEM (32h) at the ICAM school in Lille,
  - real-time simulation (20h - Image Visualization and Interaction MASTER 2 Lille1).
- Jeremie Dequidt teached:
  - Programming in C (44h - Polytech Lille),
  - Advanced Programming (14h - Polytech Lille),
  - Introduction to Android (6h - Polytech Lille),
  - Computation Theory (24h - Polytech Lille),
  - Collision Detection (4h - Master2 Univ Lille 1).
- Alexandre Bilger was the supervisor of an intern at Tohoku University,
- Zhifan Jiang teached:
  - Programming in C (32h - Polytech Lille),
  - Introduction to Database (17.76h Polytech Lille).

8.2.2. Supervision

- Séphane Cotin supervised:
  - PhD : Alexandre Bilger, *Patient-Specific Biomechanical Simulation for Deep Brain Stimulation*, Université des Sciences et Technologie de Lille - Lille I, December 2014,
  - PhD : Hugo Talbot, *Interactive Patient-Specific Simulation of Cardiac Electrophysiology*, Université des Sciences et Technologie de Lille - Lille I, July 2014,
  - PhD : Ahmed Yureidini, *Robust Blood Vessel Surface Reconstruction for Interactive Simulations from Patient Data*, Université des Sciences et Technologie de Lille - Lille I, May 2014,
  - PhD in progress : Christoph Paulus (co-supervision),
  - PhD in progress : Rosalie Plantefève (co-supervision).
- Christian Duriez supervised:

- PhD : Guillaume Kazmitcheff, *Minimal Invasive Robotics dedicated to Otological Surgery*, Université des Sciences et Technologie de Lille - Lille I, June 2014,
- PhD (co-supervision) : Alexandre Bilger, *Patient-Specific Biomechanical Simulation for Deep Brain Stimulation*, Université des Sciences et Technologie de Lille - Lille I, May 2014,
- PhD in progress : Julien Bosman,
- PhD in progress : Frédérick Largililière,
- PhD in progress : Zhifan Jiang.

- Jeremie Dequidt co-supervised the PhD in progress of Nazim Haouchine.

8.2.3. Juries

- Stéphane Cotin was in the examination committee of:
  - the PhD of Elsa Flechon (as president of the jury),
  - the PhD of Christian Herlin (as reviewer).
- Stéphane Cotin participated in the evaluation of LIRIS lab (December 2014).
- Christian Duriez was member of the jury of:
  - the PhD of Hugo Talbot (as invited member),
  - the PhD of Coralie Escande (as reviewer),
  - the PhD of Xavier Faure (as reviewer),
  - the PhD of Achille Melingui (as president of the jury).
- Jeremie Dequidt was
  - invited member in the PhD jury of Ahmed Yureidini,
  - jury member of the Android Competition for EESTEC

8.2.4. Invited talks

Séphane Cotin has been invited speaker:

- at the Advanced Laparoscopy and Computer Vision group (ISIT, UMR 6284 CNRS, Clermont Ferrand, France),
- at winter school (Medical Robotics, March 2014, Strasbourg, France),
- at summer school (July 2014, Design and Development of Medical Training Systems, Lyon, France).

Christian Duriez has been invited speaker:

- at JRL (AIST Lab) Tsukuba in October 2013,
- at BIRDS Workshop in February 2014,
- at Festo Company in march 2014,
- at ICRA workshop on Soft Robots in June 2014.

8.2.5. Special events

This year, Stéphane Cotin, team leader of the team, became research director DR1 and Christian Duriez got a position of research director during the competitive evaluation of spring 2014. Congratulations to them !

Christian Duriez also created a new research team: DEFROST working around the soft robotics: model, simulation, control and software.

Jeremie Dequidt was the team Leader of RBQT (from Polytech Lille), which has been involved in two major competitions (German Open Cup and World Cup in Brazil). Jeremie was also nvolved in the organization of the robotic competition for primary schools (CREP: *Coupe de Robotique des Ecoles Primaires) which has gathered more than 300 kids in Polytech Lille.

8.3. Popularization

8.3.1. Talk at College de France

Our project leader Stéphane Cotin made a talk at the College de France entitled "*Simulation en médecine : présent et futur*". This was done the 17th June 2014 in the scope of the Informatic chair, led by Nicholas Ayache.

8.3.2. Journée Francaise de Radiologie, JFR

The SHACRA team was par of the JFR 2014 event in Paris from the 18th to the 20th October. Hugo Talbot and Rosalie Plantefève presented their work and the project developed by the team.

8.3.3. Interaction Healthcare

The company Interaction Healthcare organized an event on the 3rd of April 2014 taking place in Paris. With this conference, the company aimed at promoting the field of serious games and virtual simulation training. At this occasion, Hugo Talbot presented the latest version of the training simulator for electrocardiology: "Electrophysiology simulation for RF-ablation of ventricular arrhythmia".

8.3.4. IHU Scientific Days

At the occasion of the IHU Scientific days, we visited the IHU Strasbourg and a talk was done by Stéphane Cotin.

8.3.5. Visit to the Mentice company

In december 2014, the training simulator for electrocardiology inteventions was presented to the Mentice company in Göteborg (Sweden). This was the opportunity to discuss our mutual technologies and compare our simulators.

8.3.6. Euratechnologie

The team presented simulations in the Inria showroom at Euratechnologie in Lille all year long. This was the opportunity to get very positive and interesting feedback from visitors.

9. Bibliography

Major publications by the team in recent years

[1] J. ALLARD, H. COURTECUISSE, F. FAURE. *Implicit FEM Solver on GPU for Interactive Deformation Simulation*, in "GPU Computing Gems Jade Edition", NVIDIA/Elsevier, October 2011, chap. 21

[2] J. ALLARD, F. FAURE, H. COURTECUISSE, F. FALIPOU, C. DURIEZ, P. G. KRY. *Volume Contact Constraints at Arbitrary Resolution*, in "ACM Transactions on Graphics (Proceedings of SIGGRAPH 2010)", August 2010, vol. 29(3), http://www.sofa-framework.org/projects/ldi

[3] S. COTIN, H. DELINGETTE, N. AYACHE. *Real-Time Elastic Deformations of Soft Tissues for Surgery Simulation*, in "IEEE Transactions on Visualization and Computer Graphics", 1999, vol. 5, n^{o} 1, pp. 62–73

[4] J. DEQUIDT, J. LENOIR, S. COTIN. *Interactive Contacts Resolution Using Smooth Surface Representation*, in "Proc. Medical Image Computing and Computer-Assisted Interventions (MICCAI)", 2007, pp. 850-857

[5] J. DEQUIDT, M. MARCHAL, C. DURIEZ, S. COTIN. *Interactive Simulation of Embolization Coils: Modeling and Experimental Validation*, in "Medical Image Computing and Computer Assisted Intervention (MICCAI)", 2008, pp. 695-702

[6] C. DURIEZ, S. COTIN, J. LENOIR, P. F. NEUMANN. *New Approaches to Catheter Navigation for Interventional Radiology Simulation*, in "Computer Aided Surgery", 2006, vol. 11, pp. 300-308

[7] C. DURIEZ, F. DUBOIS, A. KHEDDAR, C. ANDRIOT. *Realistic Haptic Rendering of Interacting Deformable Objects in Virtual Environments*, in "IEEE Transactions on Visualization and Computer Graphics", 2006, vol. 12, n^{o} 1, pp. 36–47, http://dx.doi.org/10.1109/TVCG.2006.13

[8] F. FAURE, C. DURIEZ, H. DELINGETTE, J. ALLARD, B. GILLES, S. MARCHESSEAU, H. TALBOT, H. COURTECUISSE, G. BOUSQUET, I. PETERLIK, S. COTIN. *SOFA: A Multi-Model Framework for Interactive Physical Simulation*, in "Soft Tissue Biomechanical Modeling for Computer Assisted Surgery", Y. PAYAN (editor), Studies in Mechanobiology, Tissue Engineering and Biomaterials, Springer, June 2012, vol. 11, pp. 283-321 [*DOI :* 10.1007/8415_2012_125], https://hal.inria.fr/hal-00681539

[9] A. KERDOK, S. COTIN, M. OTTENSMEYER, A. GALEA, R. HOWE, S. DAWSON. *Truth Cube: Establishing Physical Standards for Real-Time Soft Tissue Simulation*, in "Medical Image Analysis", September 2003, vol. 7, n^{o} 3

[10] V. LUBOZ, X. WU, K. KRISSIAN, C. WESTIN, R. KIKINIS, S. COTIN, S. DAWSON. *A segmentation and reconstruction technique for 3D vascular structures*, in "Medical Image Computing and Computer Assisted Intervention (MICCAI)", 2005, pp. 43-50

[11] Y. WEI, S. COTIN, F. LE, J. ALLARD, P. CHUNHUONG. *Toward Real-time Simulation of Blood-Coil Interaction during Aneurysm Embolization*, in "Medical Image Computing and Computer Assisted Intervention (MICCAI)", 2009

Publications of the year

Doctoral Dissertations and Habilitation Theses

[12] A. BILGER. *Patient-specific biomechanical simulation for deep brain stimulation*, Université des Sciences et Technologie de Lille, December 2014, https://hal.inria.fr/tel-01097488

[13] G. KAZMITCHEFF. *Dynamical modeling of the middle ear and tools organs interactions to develop a simulator applied to otological surgery*, Université Lille 1 - Sciences et Technologies, May 2014, https://hal.inria.fr/tel-01105262

[14] H. TALBOT. *Interactive Patient-Specific Simulation of Cardiac Electrophysiology*, Université des Sciences et Technologies de Lille, July 2014, https://hal.inria.fr/tel-01097201

[15] A. YUREIDINI. *Robust blood vessel surface reconstruction for interactive simulations from patient data*, Université des Sciences et Technologie de Lille - Lille I, May 2014, Rédigée au 21 janvier 2014, https://tel.archives-ouvertes.fr/tel-01010973

Articles in International Peer-Reviewed Journals

[16] H. COURTECUISSE, J. ALLARD, K. PIERRE, STEPHANE PIERRE-ALAIN. BORDAS, S. COTIN, C. DURIEZ. *Real-time simulation of contact and cutting of heterogeneous soft-tissues*, in "Medical Image Analysis", February 2014, 20 p. , https://hal.inria.fr/hal-01097108

[17] G. KAZMITCHEFF, Y. NGUYEN, M. MIROIR, F. PÉAN, E. FERRARY, S. COTIN, O. STERKERS, C. DURIEZ. *Middle-Ear Microsurgery Simulation to Improve New Robotic Procedures*, in "BioMed Research International", July 2014, 10 p. [*DOI :* 10.1155/2014/891742], https://hal.inria.fr/hal-01105278

Articles in National Peer-Reviewed Journals

[18] J. BOSMAN, C. DURIEZ, S. COTIN. *Modèle pour la simulation de tissus connectifs*, in "Revue Electronique Francophone d'Informatique Graphique", November 2014, 13 p. , https://hal.inria.fr/hal-01095301

International Conferences with Proceedings

[19] A. BILGER, E. BARDINET, S. FERNÁNDEZ-VIDAL, C. DURIEZ, P. JANNIN, S. COTIN. *Intra-operative Registration for Deep Brain Stimulation Procedures based on a Full Physics Head Model*, in "MICCAI 2014 Workshop on Deep Brain Stimulation Methodological Challenges - 2nd edition", Boston, United States, September 2014, https://hal.inria.fr/hal-01060304

[20] A. BILGER, É. BARDINET, S. FERNÁNDEZ-VIDAL, C. DURIEZ, P. JANNIN, S. COTIN. *Intra-operative Registration for Stereotactic Procedures driven by a combined Biomechanical Brain and CSF Model*, in "ISBMS - International Symposium on Biomedical Simulation", Strasbourg, France, October 2014, https://hal.inria.fr/hal-01058435

[21] A. BILGER, C. DURIEZ, S. COTIN. *Computation and Visualization of Risk Assessment in Deep Brain Stimulation*, in "MMVR 21 - Medicine Meets Virtual Reality", Manhattan Beach, California, United States, IOS Press, February 2014, https://hal.inria.fr/hal-00881694

[22] J. BOSMAN, N. HAOUCHINE, J. DEQUIDT, I. PETERLIK, S. COTIN, C. DURIEZ. *The Role of Ligaments: Patient-Specific or Scenario-Specific ?*, in "International Symposium on Biomedical Simulation ISBMS", Strasbourg, France, October 2014, https://hal.inria.fr/hal-01068077

[23] E. COEVOET, N. REYNAERT, E. LARTIGAU, L. SCHIAPPACASSE, J. DEQUIDT, C. DURIEZ. *Introducing interactive inverse FEM simulation and its application for adaptive radiotherapy*, in "MICCAI - 17th International Conference on Medical Image Computing and Computer-Assisted Intervention", Boston, United States, September 2014, https://hal.inria.fr/hal-01059667

[24] N. HAOUCHINE, J. DEQUIDT, M.-O. BERGER, S. COTIN. *Single View Augmentation of 3D Elastic Objects*, in "International Symposium on Mixed and Augmented Reality - ISMAR", Munich, Germany, September 2014, https://hal.inria.fr/hal-01056323

[25] N. HAOUCHINE, J. DEQUIDT, I. PETERLIK, E. KERRIEN, M.-O. BERGER, S. COTIN. *Towards an Accurate Tracking of Liver Tumors for Augmented Reality in Robotic Assisted Surgery*, in "International Conference on Robotics and Automation (ICRA)", Hong Kong, China, June 2014, https://hal.inria.fr/hal-01003262

[26] G. KAZMITCHEFF, H. COURTECUISSE, Y. NGUYEN, M. MIROIR, A. BOZORG-GRAYELI, S. COTIN, O. STERKERS, C. DURIEZ. *Haptic Rendering on Deformable Anatomical Tissues with Strong Heterogeneities*, in "Eurohaptics 2014", Versailles, France, Springer, June 2014, https://hal.inria.fr/hal-01025614

[27] F. LARGILLIERE, E. COEVOET, L. GRISONI, C. DURIEZ. *Real-time FEM based control of soft surgical robots*, in "SURGETICA 2014", Chambéry, France, December 2014, https://hal.inria.fr/hal-01105146

[28] R. PLANTEFEVE, N. HAOUCHINE, J. P. RADOUX, S. COTIN. *Automatic Alignment of pre and intraoperative Data using Anatomical Landmarks for Augmented Laparoscopic Liver Surgery*, in "International Symposium on Biomedical Simulation ISBMS", Strasbourg, France, October 2014, https://hal.inria.fr/hal-01068246

[29] R. PLANTEFEVE, I. PETERLIK, H. COURTECUISSE, R. TRIVISONNE, J.-P. RADOUX, S. COTIN. *Atlas-based Transfer of Boundary Conditions for Biomechanical Simulation*, in "MICCAI - 17th International Conference on Medical Image Computing and Computer Assisted Intervention", Boston, United States, September 2014, https://hal.inria.fr/hal-01070339

[30] M. SANZ-LOPEZ, J. DEQUIDT, E. KERRIEN, C. DURIEZ, M.-O. BERGER, S. COTIN. *Testbed for assessing the accuracy of interventional radiology simulations*, in "ISBMS - 6th International Symposium on Biomedical Simulation", Strasbourg, France, LNCS, Springer, October 2014, https://hal.inria.fr/hal-01059892

[31] H. TALBOT, M. LEKKAL, R. BÉSSARD-DUPARC, S. COTIN. *Interactive Planning of Cryotherapy Using Physically-Based Simulation*, in "MMVR 21 - Medicine Meets Virtual Reality - 2014", Manhattan Beach, California, United States, February 2014, https://hal.inria.fr/hal-00918200

[32] H. TALBOT, F. SPADONI, C. DURIEZ, M. SERMESANT, S. COTIN, H. DELINGETTE. *Interactive Training System for Interventional Electrocardiology Procedures*, in "6th International Symposium on Biomedical Simulation - ISBMS 2014", Strabsourg, France, October 2014, pp. 11 - 19 [*DOI :* 10.1007/978-3-319-12057-7_2], https://hal.inria.fr/hal-01078209

National Conferences with Proceedings

[33] N. HAOUCHINE, S. COTIN, J. DEQUIDT, E. KERRIEN, M.-O. BERGER. *Réalité augmentée pour la chirurgie minimalement invasive du foie utilisant un modèle biomécanique guidé par l'image*, in "Reconnaissance de Formes et Intelligence Artificielle (RFIA) 2014", France, June 2014, https://hal.archives-ouvertes.fr/hal-00988767

Conferences without Proceedings

[34] G. KAZMITCHEFF, Y. NGUYEN, M. MIROIR, E. FERRARY, S. COTIN, C. DURIEZ, O. STERKERS. *Virtual Simulation of Stapedotomy Surgery*, in "ARO 2014", San Diego, CA, United States, February 2014, https://hal.inria.fr/hal-00919984

Patents and standards

[35] S. COTIN, G. CASIEZ, M. LEKKAL, R. TRIVISONNE. *Interface de commande à distance d'un dispositif de contrôle et d'affichage d'informations dans une salle d'opération chirurgicale*, November 2014, n° 14 60867, https://hal.inria.fr/hal-01095037

References in notes

[36] J. DEQUIDT, C. DURIEZ, S. COTIN, E. KERRIEN. *Towards interactive planning of coil embolization in brain aneurysms*, in "Medical Image Computing and Computer Assisted Intervention - MICCAI 2009", London, Royaume-Uni, G.-Z. YANG, D. HAWKES, D. RUECKERT, A. NOBLE, C. TAYLOR (editors), Lecture Notes in Computer Science, Springer Berlin / Heidelberg, October 2009, vol. 5761, pp. 377-385 [*DOI :* 10.1007/978-3-642-04268-3_47], http://hal.inria.fr/inria-00430867

[37] G. SAUPIN, C. DURIEZ, S. COTIN, L. GRISONI. *Efficient Contact Modeling using Compliance Warping*, in "computer graphics international", Istanbul, Turquie, 2008, http://hal.inria.fr/hal-00844039