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

Activity Report 2012

Project-Team SHACRA

Simulation in Healthcare using Computer Research Advances

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

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THEME
Computational Medicine and Neurosciences

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Project-Team SHACRA

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SHACRA is an academic partner of the IHU MIX-Surg in Strasbourg. The IHU MIX-Surg is dedicated to Image-Guided Minimally Invasive Hybrid Surgery.

Creation of the Project-Team: January 01, 2012 .

1. Members

Research Scientists

Stéphane Cotin [Team Leader, Senior Researcher, Nancy - Grand Est, HdR]
Christian Duriez [Vice team leader, Researcher, Lille - Nord Europe]
Jérémie Allard [Researcher, Lille - Nord Europe]

Faculty Member

Jérémie Dequidt [Associate Professor, Polytech'Lille, Lille - Nord Europe]

Engineers

Bruno Carrez [SED Engineer, Inria, Lille - Nord Europe]
Mario Sanz Lopez [Engineer, USTL since July 2012, Lille - Nord Europe]

PhD Students

Hadrien Courtecuisse [Inria, until March 2012, Lille - Nord Europe]
Ahmed Yureidini [Inria co-direction with MAGRIT team, Lille - Nord Europe]
Hugo Talbot [Inria co-direction with ASCLEPIOS team, Lille - Nord Europe]
Yiyi Wei [French Ambassy, until March 2012, Lille - Nord Europe]
Vincent Majorczyk [Contrat Doctoral, USTL, Lille - Nord Europe]
Alexandre Bilger [Inria, ANR blanc ACOUSTIC, Lille - Nord Europe]
Julien Bosman [Contrat Doctoral, USTL, Lille - Nord Europe]
Guillaume Kazmitcheff [co-direction INSERM - CIFRE (entreprise Collin), Lille - Nord Europe]
Tomas Golembiovsky [Cotutelle Masaryk University, Lille - Nord Europe]
Nazim Haouchine [Inria co-direction with MAGRIT team, Lille - Nord Europe]
Zhifan Jiang [Cotutelle Ecole Centrale de Lille, Laboratoire de Mécanique de Lille, Lille - Nord Europe]
François Dervaux [Contrat Doctoral, USTL since October 2012, Lille - Nord Europe]

Post-Doctoral Fellow

Igor Peterlik [IHU Strasbourg, since Sept 2012, Nancy - Grand Est]

Administrative Assistant

Anne Rejl [shared with another team, Lille - Nord Europe]

2. Overall Objectives

2.1. Team Overview

The SHACRA project-team can be seen as an evolution of the scientific activities of the ALCOVE project-team, but its genesis also derives from other initiatives such as the large scale initiative on medical simulation (*Inria AE SOFA InterMedS*), started two years ago, and the development program for the SOFA framework. These different projects have helped to strengthen our expertise and refine our scientific objectives. A common element among these objectives is the notion of interaction. It implies that the simulations we develop are computed in real (or near real) time, and that the presence of a user in the loop is accounted for (through the use of dedicated hardware devices, haptic feedback and robust algorithms). This requires to develop accurate models, coupled with fast and robust computational strategies. The research directions we propose to follow essentially aim at improving the realism and fidelity of interactive simulations of medical procedures. This increase in realism will permit to address new clinical applications, in particular pre-operative planning and per-operative guidance, that currently rely on imaging techniques, but could greatly benefit from simulation techniques, thus enabling what we could call "*simulation-guided therapy*". 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. They include real-time biophysical models (to define new models describing soft tissue deformation or physiological phenomena, and to develop computational strategies to enable real-time computation even with the increase in complexity of future models), models of therapy (to describe the action of medical devices on the anatomy whether this action is mechanical, electrical or chemical), and interaction models (to account for a variety of constraints between anatomical structures as well as tissue-tool interactions). The SOFA framework will be used to synthesize our various contributions and integrate them in a series of prototypes. These prototypes will span across several clinical areas and will serve as a basis for transitioning from training to planning to guidance.

2.2. Challenges

2.2.1. Real-Time Accurate 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 biophysical phenomena such as soft-tissue deformation, fluid dynamics, electrical propagation, or heat transfer. These models will help to 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 (near) real-time computation.

2.2.2. Multi-Model Simulations

The notion of multi-model simulation encompasses two ideas. First, it captures the idea that organs are not isolated in the body and therefore are constantly interacting with the surrounding anatomy through various types or constraints. Second it translates the need to build complex models from "*simpler*" ones that interact with each other at a functional level, forming coupled systems (of which vascularized organs or an electro-mechanical model of the heart are good examples). As we start building larger simulations or models, computational efficiency will become of prime importance. That is why a part of our research consist in developing new strategies for parallel computing that will be adapted for multi-model simulations.

2.2.3. Simulation-guided Therapy

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 related to image-guided therapy (e.g. fusion of multi-modality images, registration, segmentation, reconstruction, ...) but the principal one consists in aligning pre-operative images onto the patient. As most procedures deal with soft-tissues, elastic registration techniques are necessary to perform this step. Recently, registration techniques started to account for soft tissue deformation using physically-based methods [30]. Yet, several limitations still hinder the use image-guided therapy in clinical routine. First, as registration methods become more complex, their computation times increase, thus lacking responsiveness. Second, as we have seen in previous sections, many factors influence the deformation of soft-tissues, from patient-specific material properties to boundary conditions with surrounding anatomy. A typical illustration of this problem, in the field of neurosurgery, is the brain shift that takes place when the skull is opened and the intracranial pressure drops [37]. It is clear that several of the techniques we are developing for interactive simulation could be applied to pre-operative images in order to provide added feedback during a procedure. In particular, several aspects, besides modeling brain tissue deformation, come into play during brain shift, such as contact between the brain and the skull, the influence of the vascular network, etc. We have already illustrated this potential in the context of coil embolization [28].

2.3. Highlights of the Year

2.3.1. Two full papers at MICCAI'2012 in Nice

Two full papers have been accepted in the International Conference on Medical Imaging Computing and Computer Assisted Intervention (MICCAI, ERA's Ranking A).

2.3.2. IHU Mix-Surg and Haystack Project

The team is involved in the creation of the IHU Mix-Surg in Strasbourg, a new institute dedicated to minimally invasive therapies, guided by image and simulation. It involves interdisciplinary expertise of medical groups, academic partners and strong industry partnerships. IHU has provided financial support for a project named Haystack (image guided surgery for brachyterapy).

2.3.3. HelpMeSee Project

The team has been involved on a project funded by the non-governmental organization *HelpMeSee* [1]. HelpMeSee aims at providing ways to treat cataract surgery in third world countries. Their main objective is to develop a simulator to train surgeons. Shacra has been involved for its expertise in real-time simulation of soft anatomical structures.

3. Scientific Foundations

3.1. Biomechanical Modeling

3.1.1. 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 such an approach [24], [27] 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 rely on linearized constitutive laws.

An important part of our research is dedicated to the development of new, more accurate models that remain 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. Yet, patient-specific planning or per-operative guidance also requires the models to be parametrized with patient-specific biomechanical data. Very little work has been done in this area, in particular when tissue properties need to be measured in vivo non-invasively. New imaging techniques, such as Ultrasound Elastography or Magnetic Resonance Elastography, could be used to this end [23]. We are currently studying the impact of parametrized patient-specific models of the liver in the context of the PASSPORT european project. This will be used to provide information about the deformation, tissue stiffness and tumor location, for various liver pathologies.

[1] http://www.helpmesee.org

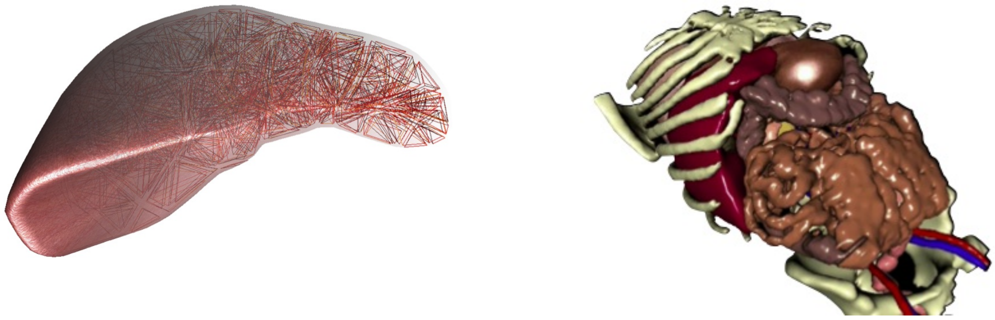

Figure 1. Biomechanical models of organs, based on the Finite Element Method and elasticity theory. Left: a model of the liver based on tetrahedral elements and small strain elasticity. Right: several organ models from a patient dataset combined to create a realistic abdominal anatomy.

3.1.2. Biomechanical modeling of hollow structures

A large number of anatomical structures in the human body are vascularized (brain, liver, heart, kidneys, ...) and recent interventions (such as interventional radiology) rely on the vascular network as a therapeutical pathway. It is therefore essential to model the shape and deformable behavior of blood vessels. This will be done at two levels. Global deformation of a vascular network: we have demonstrated previously [9] that we could recover the shape of thousands of vessels from medical images by extracting the centerline of each vessel (see Figure 2). The resulting vascular skeleton can be modeled as a deformable (tree) structure which can capture the global aspects of the deformation. More local deformations can then be described by considering now the actual local shape of the vessel. Other structures such as aneurysms, the colon or stomach can also benefit from being modeled as deformable structures. For this we will rely on shell or thin plate theory. We have recently obtained very encouraging results in the context of the Ph.D. thesis of Olivier Comas [26]. Such local and global models of hollow structures will be particularly relevant for planning coil deployment or stent placement, but also in the context of a new laparoscopic technique called NOTES which uses a combination of a flexible endoscope and flexible instruments. Obtaining patient-specific models of vascular structures and associated pathologies remains a challenge from an image processing stand point, and this challenge is even greater once we require these models to be adapted to complex computational strategies. To this extend we will pursue our collaboration with the MAGRIT team at Inria (through a PhD thesis starting in January 2010) and the Massachusetts General Hospital in Boston.

3.1.3. Blood Flow Simulation

Beyond biomechanical modeling of soft tissues, an essential component of a simulation is the modeling of the functional interactions occurring between the different elements of the anatomy. This involves for instance modeling physiological flows (blood flow, air flow within the lungs...). We particularly plan to study the problem of fluid flow in the context of vascular interventions, such as the simulation of three-dimensional turbulent flow around aneurysms to better model coil embolization procedures. Blood flow dynamics is starting to play an increasingly important role in the assessment of vascular pathologies, as well as in the evaluation of pre- and post-operative status. While angiography has been an integral part of interventional radiology procedures for years, it is only recently that detailed analysis of blood flow patterns has been studied as a mean to assess complex procedures, such as coil deployment. A few studies have focused on aneurysm-related hemodynamics before and after endovascular coil embolization. Groden et al. [31] constructed a simple geometrical model to approximate an actual aneurysm, and evaluated the impact of different levels of coil packing on the flow and wall pressure by solving Navier-Stokes equations, while Kakalis et al. [33] relied on patient-specific data to get more realistic flow patterns, and modeled the coiled aneurysm as a porous medium. As these studies aimed at accurate Computational Fluid Dynamics simulation, they rely on commercial software, and the computation times (dozens of hours in general) are incompatible with interactive simulation or even clinical practice. Generally speaking, accuracy and efficiency are two significant pursuits in numerical calculation, but unfortunately very often contradictory.

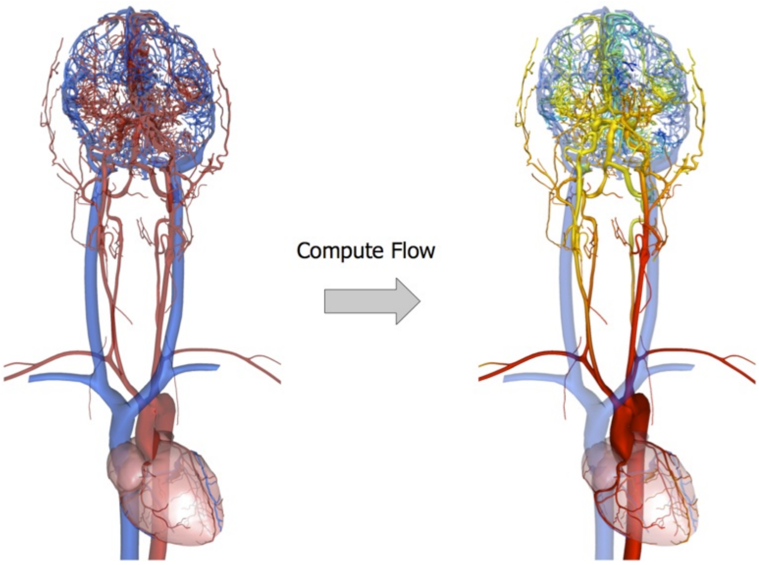

Figure 2. Blood flow and pressure distribution in the cerebrovascular system. The arterial vascular network is composed of more than 3,000 vessels, yet the computation is performed in real-time.

With the Ph.D. thesis of Yiyi Wei, we have recently started the development of a new technique for accurately computing, in near real-time, the flow of blood within an aneurysm, as well as the interaction between blood and coils. In this approach we rely on the Discrete Exterior Calculus method to obtain an ideal trade-off between accuracy and computational efficiency. Although still at an early stage, these results show that our approach can accurately capture the main characteristics of the complex blood flow patterns in and around an aneurism. The model also takes into account the influence of the coil on the blood flow within the aneurysm. The main difference between our approach and many other work done by internationally renowned teams (such as REO team at Inria or the Computer Vision Laboratory at ETH) comes from the importance we place in the computational efficiency of the method. To some extent our approach is similar to what has been done to obtain real-time finite element methods. We are essentially trying to capture the key characteristics of the behavior for a particular application. This is well illustrated by the work we started on flow modeling, which received an award in September 2009 at the selective conference on Medical Image Computing and Computer Assisted Interventions [10]. We will pursue this direction to accurately model the local flow in a closed domain (blood vessel, aneurysm ventricle, ...) and combine it with some of our previous work describing laminar flow across a large number of vessels [38] in order to define boundary conditions for the three-dimensional model.

3.2. Biomechanical Systems

3.2.1. Constraint models and boundary conditions

To accurately model soft tissue deformations, the approach must account for the intrinsic behavior of the target organ, but also for its biomechanical interactions with surrounding tissues or with medical devices. While the biomechanical behavior of important organs (such as the brain or liver) has been well studied, few work exists regarding the mechanical interactions between the anatomical structures. For tissue-tool interactions, most approaches rely on a simple contact models, and rarely account for friction. While this simplification can produce plausible results in the case of an interaction between the end effector of a laparoscopic instrument and the surface of an organ, it is generally an incorrect approximation. As we move towards simulations for planning or rehearsal, accurately modeling contacts will take an increasingly important place. We have recently shown in [28] and [29] that we could compute, in real-time, complex interactions between a coil and an aneurysm, or between a flexible needle and soft-tissues. In laparoscopic surgery, the main challenge lies in the modeling of interactions between anatomical structures rather than between the instruments and the surface of an organ. During the different steps of a procedure organs slides against each other, while respiratory, cardiac and patient motion also generate contacts. Modeling these multiple interactions becomes even more complex when different biomechanical models are used to characterize the various soft tissues of the anatomy. Consequently, our objective is to accurately model resting contacts with friction, in a heterogeneous environment (spring-mass models, finite element models, particle systems, rigid objects, etc.). When different time integration strategies are used, a challenge lies in the computation of contact forces in a way that integrity and stability of the overall simulation are maintained. Our objective is to work on the definition of these various boundary conditions and on new resolution methods for such heterogeneous simulations. In particular we will investigate a simulation process in which each model continues to benefit from its own optimizations while taking into account the mechanical couplings due to interactions between objects.

3.2.2. Vascularized anatomy

From a clinical standpoint, several procedures involve vascularized anatomical structures such as the liver, the kidneys, or the brain. When a therapy needs to be applied on such structures, it is currently possible to perform a procedure surgically or to use an endovascular approach. This requires to characterize and model the behavior of vessels (arteries and veins) as well as the behavior of soft tissue (in particular the parenchyma). Another challenge of this research will be to model the interactions between the vascular network and the parenchyma where it is embedded. These interactions are key for both laparoscopic surgery and interventional radiology as they allow to describe the motion of the vessels in a vascularized organ during the procedure. This motion is either induced by the surgical manipulation of the parenchymal tissue during surgery or by respiratory, cardiac or patient motion during interventional radiology procedures. From a biomechanical standpoint, capillaries are responsible for the viscoelastic behavior of the vascularized structures, while larger vessels have a direct impact on the overall behavior of the anatomy. In the liver for instance, the apparent stiffness of the organ changes depending on the presence or absence of large vessels. Also, the relatively isotropic nature of the parenchyma is modified around blood vessels. We propose to model the coupling that exists between these two different anatomical structures to account for their respective influence. For this we will initially rely on the work done during the Ph.D. thesis of Christophe Guebert (see ([32] for instance) and we will also investigate coupling strategies based on degrees of freedom reduction to reduce the complexity of the problem (and therefore also computation times). Part of this work is already underway in the context of the PASSPORT european project with IRCAD and soft tissue measurements will be performed in collaboration with the biomechanics laboratory at Strasbourg University.

3.2.3. Parallel Computation

Although the past decade has seen a significant increase in complexity and performance of the algorithms used in medical simulation, major improvements are still required to enable patient-specific simulation and planning. Using parallel architectures to push the complexity of simulated environments further is clearly an approach to consider. However, interactive simulations introduce new constraints and evaluation criteria, such as latencies, multiple update frequencies and dynamic adaptation of precision levels, which require further investigation. New parallel architectures, such as multi-cores CPUs, are now ubiquitous as the performances achieved by sequential units (single core CPUs) stopped to regularly improve. At the same time, graphical processors (GPU) offer a massive computing power that is now accessible to non-graphical tasks thanks to new general-purposes API such as CUDA and OpenCL. GPUs are internally parallel processors, exploiting hundreds of computing units. These architectures can be exploited for more ambitious simulations, as we already have demonstrated in a first step by adding support for CUDA within the SOFA framework. Several preliminary results of GPU-based simulations have been obtained, permitting to reach speedup factors (compared to a single core GPU) ranging from 16x to 55x. Such improvements permit to consider simulations with finer details, or new algorithms modeling biomechanical behaviors more precisely. However, while the fast evolution of parallel architectures is useful to increase the realism of simulations, their varieties (multi-core CPUs, GPUs, clusters, grids) make the design of parallel algorithm challenging. An important effort needs to be made is to minimize the dependency between simulation algorithms and hardware architectures, allowing the reuse of parallelization efforts on all architecture, as well as simultaneously exploiting all available computing resources present in current and future computers. The largest gains could be achieved by combining parallelism and adaptive algorithms. The design and implementation of such a system is a challenging problem, as it is no longer possible to rely on pre-computed repartition of datas and computations. Thus, further research is required in highly adaptive parallel scheduling algorithms, and highly efficient implementation able to handle both large changes in computational loads due to user interactions and multi-level algorithms, and new massively parallel architectures such as GPUs. A direction that we are also investigating is to combine multi-level representations and locally adaptive meshes. Multi-level algorithms are useful not only to speedup computations, but also to describe different characteristics of the deformation at each level. Combined with local change of details of the mesh (possibly using hierarchical structures), the simulation can reach a high level of scalability.

4. Application Domains

4.1. Clinical Applications

Some of the scientific challenges described previously can be seen in a general context (such as solving constraints between different types of objects, parallel computing for interactive simulations, etc.) but often it is necessary to define a clinical context for the problem. This is required in particular for defining the appropriate assumptions in various stages of the biophysical modeling. It is also necessary to validate the results. This clinical context is a combination of two elements: the procedure we attempt to simulate and the objective of the simulation: training, planning or per-operative guidance. Below are a series of applications we plan to develop. The choice of these applications is not random: the clinical procedures we target are all technically challenging, they highlight various parts of our research, and often they represent an ideal testbed for transitioning from training to planning to guidance. It is important also to note that developing these applications raises many challenges and as such this step should be seen as an integral part of our research. It is also through the development of these applications that we can communicate with physicians, and validate our results. SOFA will be used as a backbone for the integration of our research into clinical applications.

4.1.1. Interventional radiology

Over the past twenty years, interventional methods such as angioplasty, stenting, and catheter-based drug delivery have substantially improved the outcomes for patients with vascular disease. Pathologies that used to require a surgical procedure can now be treated in a much less invasive way. As a consequence, interventional radiology procedures represent an increasing part of the interventions currently performed, with more than 6 million patients treated every year in Europe and about 5 millions the United States. However, these techniques require an intricate combination of tactile and visual feedback, and extensive training periods to attain competency. To reinforce the need to reach and maintain proficiency, the FDA recently required that US physicians go through simulation-based training before using newly developed carotid stents. Besides simulation for training, interventional radiology is a perfect target to illustrate the potential of planning and rehearsal of procedures. As an initial step in this direction, Alcove and Magrit were partners in an ARC project (Simple) to develop a planning tool for the treatment of aneurysms using coils. This collaboration still goes on after the end of the ARC, and led to a series of papers in key conferences [5] [28], [34], [21].

4.1.1.1. Interventional neuro-radiology

We will continue the development of our simulation and planning system for interventional radiology, with two principal clinical partners: Massachusetts General Hospital in Boston and University Hospital in Nancy. We have completed the integration in SOFA of improved versions of algorithms for describing the behavior of catheters, guide-wires, coils, as well as the interactive simulation of fluoroscopic images, the modeling of complex contacts. Our future efforts will focus on the development of an advanced planning system for interventional radiology, in particular for coil embolization. This will require the integration of new methods of reconstruction of vascular anatomy from medical images (in collaboration with the MAGRIT team). We will also add our recent results on blood flow simulation in aneurysms.

4.1.1.2. Interventional cardiology using radio-frequency ablation

Cardiac arrhythmias (or dysrhythmias) are problems that affect the electrical system of the heart muscle, producing abnormal heart rhythms, and causing the heart to pump less effectively. About 5% of people over 40 years old are affected by this pathology, with a rather high morbidity rate. Radio-frequency ablation is a non-surgical procedure that has been used for about 15 years to treat tachyarrhythmias, i.e. rapid, uncoordinated heartbeats. The procedure is performed by guiding a catheter with an electrode at its tip to the area of heart muscle where there is an accessory pathway. The catheter is guided under fluoroscopic imaging. When the catheter is positioned at the site where cells give off the electrical signals that stimulate the abnormal heart rhythm, a low radio-frequency energy is transmitted to the pathway. This destroys heart muscle cells within a very small area near the tip of the catheter and stops the area from conducting the extra impulses that caused the arrhythmia. In this context, a simulation system would be able to provide added value in two main areas: 1) to train physicians in the early stages of their apprenticeship and 2) to provide quantitative information during the planning phase of a complex procedure, using patient-specific data. Most aspects of this simulation will rely on components developed during our research program but we will also extend our collaboration with the ASCLEPIOS team and the CardioSense3D project on the modeling of the heart the Cadiosense3D project. This involves an important integration task, and it will also validate the reusability aspects of the code developed within SOFA.

4.1.2. Minimally-invasive surgery

4.1.2.1. Laparoscopic hepatic resection

The liver is one of the major organs in the human body. It is in charge of more than 100 vital functions. Because of its many functions, its pathologies are also varied, numerous and unfortunately often lethal. This is for instance the case of hepatitides which today affect about 300,000 people in France for hepatitis B and 600,000 people for hepatitis C. The most advanced state of evolution of these pathologies is generally cirrhosis followed by cancer, which represents the third cause of cancer related death. In 2005, 14,267 liver cancer cases and 20,497 cirrhosis cases have been diagnosed in France. The surgical solution remains the option offering the best success rate for these pathologies. More than 7,000 surgical interventions have been carried out on the liver in 2005 and partial resection of the liver remains the most common approach. In this context, the ability to train surgeons, and to be able to plan complex procedures using computer-based simulations, would be a formidable help to the current apprenticeship model: “See One, Do One, Teach One”. Right now, only a few commercial systems are available to the medical community, and they are limited to basic skills training. Developing a realistic simulation system that could be used to plan and rehearse procedures would be a very important step in the introduction of new training paradigms in medicine. This is the main objective of the PASSPORT european project in which we are actively contributing at two levels. First, our research results on biomechanical modeling of solid organs and on coupling will be used to propose a realistic model of the deformation of the liver and its vascular network. Second, SOFA has been chosen in this project as the software for integrating all results from the different partners. Both aspects will help validate our models, test SOFA and obtain feedback from the clinicians.

4.1.2.2. Ophthalmology and cataract surgery

A cataract is an opacity in the natural lens of the eye. It represents an important cause of visual impairment and, if not treated, can lead to blindness. It is actually the leading cause of blindness worldwide, and its development is related to aging, sunlight exposure, smoking, poor nutrition, eye trauma, and certain medications. The best treatment for this pathology remains surgery. Cataract surgery has made important advances over the past twenty years, and in 2005, more than 5 million people in the United States and in Europe underwent cataract surgery. Most cataract surgeries are performed using microscopic size incisions, advanced ultrasonic equipment to fragment cataracts into tiny fragments, and foldable intraocular lenses to minimize the size of the incision. All these advances benefit the patient, but increase training requirements for eye surgeons. At the end of 2007, we started the development of a new training system for cataract surgery. The main objectives of this simulation are to reproduce with great accuracy the three main steps of cataract surgery: 1) capsulorhexis 2) phacoemulsification and 3) implantation of an intraocular lens. We have already started the development of this simulation. The main research effort went in the choice of appropriate deformable models for the lens and lens capsule. An important effort also went into the development of topological changes corresponding to the capsulorhexis and phacoemulsification [20]. The modeling of the intraocular implant and its deployment in the capsule has been published to the major conference in medical simulation [26].

4.1.2.3. Neurosurgery and deep brain stimulation

Deep brain stimulation (DBS) is a neurosurgical treatment which stimulates the brain with low electrical signals. The signals reorganize the brain's electrical impulses (similarly as what was presented above for radio-frequency ablation for cardiac problems). This results in major improvements in several pathologies such as Parkinson disease. The principle of the procedure is the following: a thin, insulated wire lead with several electrodes at the tip is surgically implanted into the affected area of the brain. A wire runs under the skin to a battery-operated pulse generator implanted near the collarbone. The generator is programmed to send continuous electrical pulses to the brain. To implant the electrodes, a neurosurgeon uses a stereotactic head frame and magnetic resonance or computed tomography imaging to map the brain and pinpoint the problem area. The main difficulty in this procedure comes from the deformation of the brain (small brain shift when the skull is opened, and local deformation of the brain due to the insertion of the electrode) and the deflection of the electrode itself during and after the procedure. This results in a difference between the planned target and the location of the end effector of the electrode. Our main objective is to use our work on soft tissue deformation, vascularized structures, as well as our recent results on constraint solving between soft tissues and flexible devices [29]. This work will be done in collaboration with the VISAGES team and we will dedicate an important effort in validating our results, analyzing post-operative medical images, and interacting with surgeons. This project has a strong potential as DBS is being increasingly used yet most research groups only consider non deformable planning systems (geometrical planning). Our proposal could make a important difference in the accuracy of the planning as it takes into account the biophysics of the brain.

5. Software

5.1. SOFA

SOFA, the 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 many academic and industrial sites. Over the last two years, the SOFA framework has evolved from an informal collaborative work between the Sim Group at CIMIT, the Alcove, Asclepios and Evasion teams at Inria into a more structured development project. By proposing a unique architecture allowing the integration of the multiple competencies required for the development of a medical training system, we believe it will be possible to accelerate and foster research activities in the field of interactive medical simulation. The main objectives of the SOFA framework are:

- Simplify the development of medical simulation systems by improving interoperability
- Evaluate and validate new algorithms
- Accelerate the prototyping of simulation systems by promoting component reusability
- Promote collaboration between research groups
- Facilitate technology transfer between research and industry

Our activities around the SOFA framework will be twofold. We will remain one of the leading teams contributing to the design of SOFA, the development of its architecture and its distribution to research groups and industrial partners. In addition, we will use SOFA as a core element of most of our simulations, as a mean to facilitate the integration of results from partners of the national initiative, and to simplify the development of prototypes of simulation systems. For the past few years, there have been a few attempts at designing software toolkits for medical simulation. Examples include [36], GiPSi [25], SPORE [35] or SSTML [22]. These different solutions aim at the same goal: providing an answer (usually Open Source) to the various challenges of medical simulation research and development. Although our aim is similar, we propose a different approach, through a very modular and flexible software framework, while minimizing the impact of this flexibility on the computation overhead. To achieve these objectives, we have developed a new architecture that implements a series of innovative concepts. Also, by developing the SOFA framework collaboratively with scientific experts in the different areas of medical simulation, we believe we can provide state-of-the-art solutions that are generically applicable, yet computationally efficient. The following sections describe in more details our approach to the development of this framework, from a technical standpoint and from the perspective of a collaborative work.

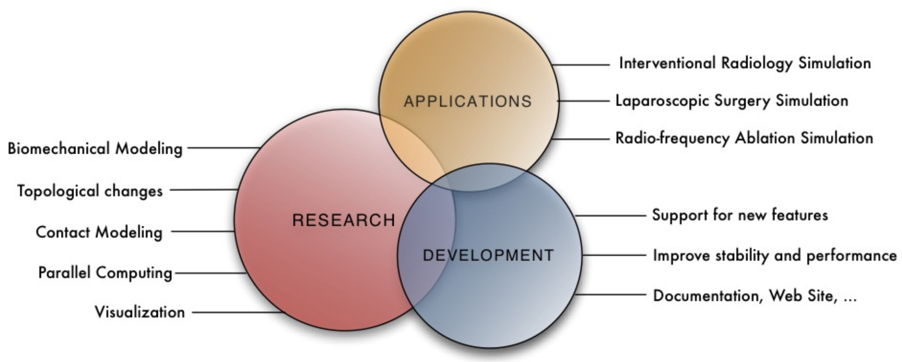

Figure 3. Multidisciplinary research and development of the SOFA framework need to take place simultaneously to quickly advance research in the field of computer-based interactive medical simulation

5.1.1. SOFA architecture

Medical simulation relies on a variety of interacting physics-based models, such as rigid structures (e.g. bones), deformable structures (e.g. soft-tissues) and fluids. It also involves anatomical representations through geometrical models, used for visual rendering, collision detection or meshes that will support various computational models. Finally, interactions between these different models need to be efficient, accurate and capable of handling a variety of representations. In some instances, a hierarchy also exists between the various anatomical structures, and needs to be taken into account in the description of the simulated environment. The design of the SOFA architecture, by supporting these various requirements, brings the flexibility needed for academic research. Yet, its very efficient implementation makes it also suitable for professional applications and potentially for product development. This architecture relies on several innovative concepts, in particular the notion of multi-model representation. In SOFA, most simulation components (deformable models, collision models, medical devices, etc.) can have several representations, connected through a mechanism called mapping. Each representation is optimized for a particular task (e.g. collision detection, visualization) while at the same time improving interoperability by creating a clear separation between the functional aspects of the simulation components. As a consequence, it is possible to have models of very different nature interact together, for instance rigid bodies, deformable objects, and fluids. This is an essential aspect of SOFA, as it will help the integration of new research components. This modular design also facilitates the rapid prototyping of simulation systems, allowing various combinations of algorithms to be tested and compared against each other. At a finer level of granularity, we also propose a decomposition of physical models (i.e. any model that behaves according to the laws of physics) into a set of basic components. In the case of (bio)mechanical models, which are computationally expensive, many strategies have been used to improve computation times or to reduce the complexity of the original model: linear elastic models have often been used instead of more complex non-linear representations, mass-spring methods as an alternative to finite element methods, etc. Each of these simplifications induces drawbacks, yet the importance of these drawbacks depends largely on the context in which they are applied. It becomes then very difficult to choose which particular method is most likely to provide the best results for a given simulation. To address this issue in SOFA we have introduced a finer level of granularity which permits to independently test and compare each component, such as time integration schemes, to see the change in performance or robustness of the simulation, or to test different constitutive models. These changes can be made in a matter of seconds, without having to recompile any of the code, by simply editing an XML file.

5.1.2. Current Results

Version 1.0 RC1 of SOFA was released in December 2011 but since October 2012, SOFA is now available through a public and anonymous SVN. More than 137,000 downloads of SOFA have been counted as of November 2012. More than 70 researchers, students, engineers have contributed at various degrees to SOFA, for a total of about 1,200,000 lines of code. Currently, thanks to its advanced architecture, SOFA allows to:

- Create complex and evolving simulations by combining new algorithms with existing algorithms
- Modify most parameters of the simulation by simply editing a XML file
- Build complex models from simpler ones using a scene-graph description
- Efficiently simulate the dynamics of interacting objects using abstract equation solvers
- Reuse and easily compare a variety of available methods
- Transparently parallelize complex computations using semantics based on data dependencies
- Use new generations of GPUs through the CUDA API to greatly improve computation times
- Use embedded Python environment to create interactive and parametric scenes, and interact with 3rd party software

Various results and information can be obtained on the SOFA website at http://www.sofa-framework.org. Most of the current results are generic and only aim at validating the different aspects of the SOFA framework. Developments of complex medical simulations have recently started, in particular in the areas of ophthalmic surgery and interventional radiology. We have also started a collaboration with a few companies (Digital Trainers, Didhaptics, B.K.) which are in the process of developing medical applications based on SOFA.

6. New Results

6.1. Non-Rigid Augmented Reality for Hepatic Surgery

Hepatic resection and tumors removal approaches remains a major challenge. Despite the use of new minimally invasive techniques which has several advantages such as precision, decreased blood loss, quicker healing time and less pain, the lack of informations due to poor depth perception and direct contact lost leads the surgeons and the research groups to use Augmented Reality to overcome these issues. Augmented Reality is the visual overlay of computers-generated images over real world images. This technique can be used to overlay vessels, tumors and cutting planes performed on the pre-operative data (3D reconstruction from CT or MR scan) onto the laparoscopic video per-operatively. However, current techniques are limited to a rigid registration of the pre-operative liver anatomy onto the intra-operative image, and often this registration is not performed automatically. Our objective is to develop a real-time, non-rigid registration and tracking of the intra and pre-operative liver data.

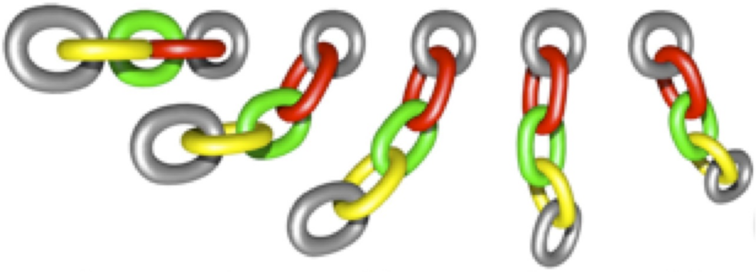

Figure 4. Animation of a chain combining a FEM model, a mass-spring model, a FFD grid, and a rigid body. This example is a perfect illustration of the flexibility of SOFA. Not only several algorithms for rigid or deformable bodies can be part of the same simulation, but they can also interact in a physically correct manner. No constraints between links were pre-defined, instead we relied on collision detection and stiff contact forces to handle the contacts. Using implicit integrator handling dynamically-created groups of interacting objects resulted in a stable simulation

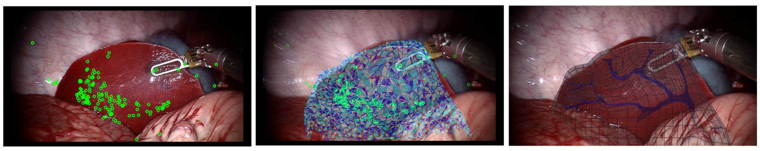

Figure 5. Non-rigid augmentation of a vascular network of a porcine liver : (left) The liver tracking. (Middle) Biomechanical model of the liver under deformation. (Right) Overlaid vascular network.

6.2. Implicit Modeling of Vascular Trees

Many clinical applications require a vessel segmentation process that is able to both extract the centerline and the surface of the blood vessels. However, noise and topology issues (such as kissing vessels) prevent existing algorithms from being able to easily retrieve such a complex system as the brain vasculature. We propose a new blood vessel tracking algorithm that 1) detect the vessel centerline; 2) provide a local radius estimate; and 3) extracts a dense set of points at the blood vessel surface. This algorithm is based on a RANSAC-based robust fitting of successive cylinders along the vessel. Our method was validated against the Multiple Hypothesis Tracking (MHT) algorithm on 10 3DRA patient data of the brain vasculature. Over 30 blood vessels of various sizes were considered for each patient. Our results demonstrated a greater ability of our algorithm to track small, tortuous and touching vessels (96% success rate), compared to MHT (65% success rate). The computed centerline precision was below 1 voxel when compared to MHT. Moreover, our results were obtained with the same set of parameters for all patients and all blood vessels, except for the seed point for each vessel, also necessary for MHT. The proposed algorithm is thereafter able to extract the full intracranial vasculature with little user interaction.

In the context of computer-based simulation, contact management requires an accurate, smooth, but still efficient surface model for the blood vessels. A new implicit model is proposed, consisting of a tree of local implicit surfaces generated by skeletons (*blobby models*). The surface is reconstructed from data points by minimizing an energy, alternating with an original blob selection and subdivision scheme. The reconstructed models are very efficient for simulation and were shown to provide a sub-voxel approximation of the vessel surface on 5 patients.

6.3. Riskmaps in DBS

As discussed in previous sections, Deep Brain Stimulation is a neurosurgical treatment that provides remarkable benefits in neurological movement and affective disorders. It consists in the implantation of a wired electrode deep into the brain. However, the accuracy of the placement is difficult due to brain shifts occuring during the procedure. Due to a potential risk of hemorrhage during the implantation, we specially investigated the brain shift induced motion of the vascular structures. We proposed a method to estimate this motion, based on a physics simulation that consider brain deformation, cerebrospinal fluid and multiple interactions, such as brain-skull contacts etc. The aim is to take it into account during the pre-operative planification step. Thus, we developped a brain-shift aware risk map. It estimate the risk for a trajectory to dissect a vessel. It could help surgeons to choose a safer trajectory for the electrode, and then avoid hemorrhages. The next steps is the use of more complex deformation models.

6.4. Electro Physiology

Cardiac arrhythmia is a very frequent pathology that comes from an abnormal electrical activity in the myocardium. This Ph.D. aims at developing a training simulator for interventional radiology and thermo-ablation of these arrhythmias. The latest improvements lead on electrophysiology simulation (using GPU computing) allowed us to reach real-time performance. The issue of fast electrophysiology was a major bottleneck in the development of our simulator.

This new result enabled us to couple the cardiac eletrophysiology with cardiac mechanical models, thus leading to an interactive framework. Our tractable simulation can therefore simulate a patient-specific electrophysiology and then compute the associated cardiac motion using an electromechanical model.

Moreover, the electrophysiology simulation has been also coupled with a navigation simulation. This is still a work in progress. The implementation of more complex models, such as bidomain models, is also in progress.

6.5. Shells

Many tissues in human body have thin structure and may be seen as surfaces or at least be modeled as such. Deformation modeling of surfaces is a topic with wide area of applications especially in computer graphics. However, many of the previously presented techniques are not applicable to the area of surgical simulations where a more physically based approach is desired.

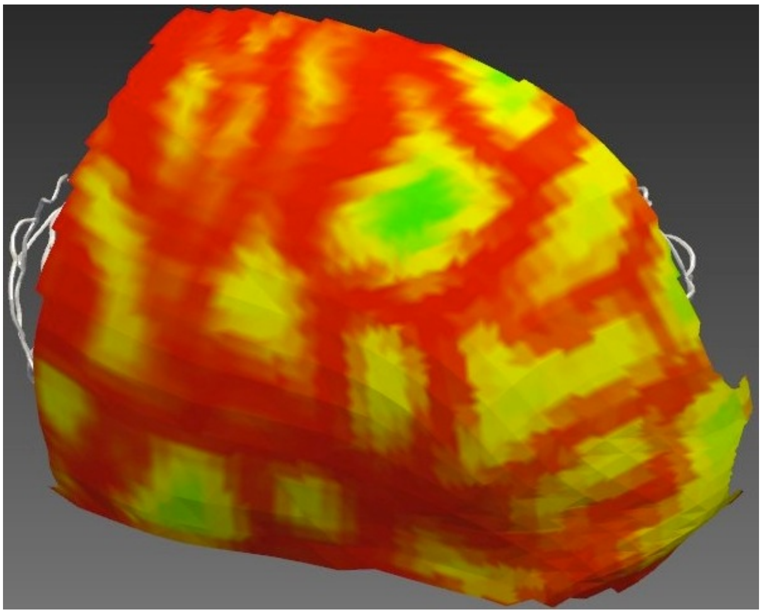

Figure 6. Brain-shift aware risk map

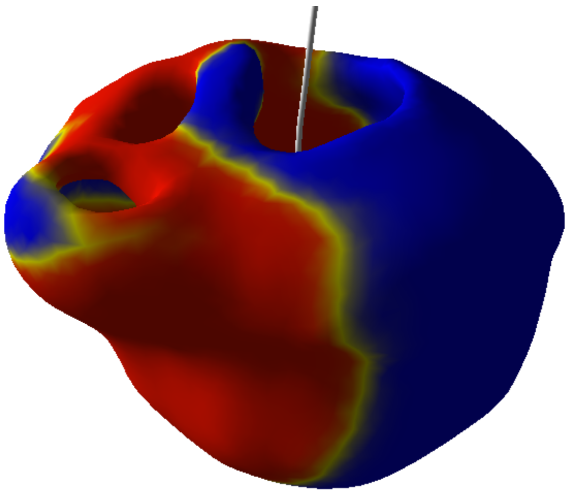

Figure 7. Cardiac electrophysiology computed on a patient-specific geometry

To address this problem we present a new model of shell elements based on the formulation of Bézier triangles. To reduce the number of necessary degrees of freedom a kinematic link between nodes inside the element is defined. Furthermore, using implicit integration scheme allows us to achieve interactive frame rate of the simulation.

The applicability of the model has been validated on a prototype of simulator for preoperative planning of surgery of congenital heart diseases.

6.6. Interaction simulation between fluid film and deformable solids

Body fluids are a major constituent of the human body as well by their volume as by their functions. Besides the blood and the lymphatic liquid, many other liquids are present in the body and they have important functions such as lubrication or shock absorption. In this work, we are more particularly interested in the fluids being in the interface between two anatomical structures. We present a method making it possible to simulate the phenomena of interaction between a fluid film and surfaces between which it is forced. The approach that we propose is based on a fluid model and its mechanical coupling with deformable surfaces. According to the pressure of the fluid and the stiffness of the deformable solids in contact with the fluid, various behaviours are expected. Our preliminary results show that it is possible to simulate the main features of these behaviours. Furthermore, the approaches chosen for the fluid model, the deformable model and the coupling between both, are compatible with real time simulations.

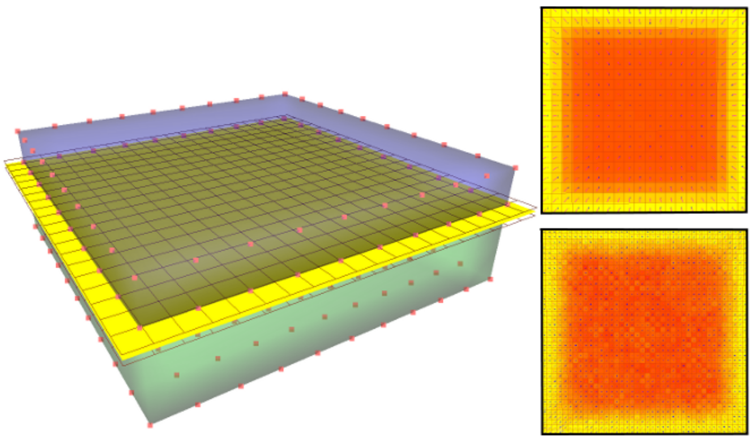

Figure 8. The fluid is between a rigid solid (green) and a deformable solid (blue). The deformable solid is constraint at the edges. Right: the height map of the fluid (yellow minimum and red maximum height).

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

7.1.1. HelpMeSee and Sensegraphics

The swedish company Sensegraphics and the NGO HelpMeSee have signed for 2 contracts for technology transfer. The contract focus on the design of a simulator to treat cataract surgery using the MSICS (Manual small incision cataract surgery) technique.

7.1.2. Digital Trainers

The company Digital Trainers has signed a two year contract and a two year license with our group for the transfer of our suture simulation technology. The contract aims at improving the simulation by using an adaptive model for the suture thread and continuous constraints for the interaction with the soft tissues. Haptic feedback will also be investigated.

7.1.3. Collin

We have started a collaboration with INSERM - UMR-S 867 (minimal invasive and robotized otological surgery) Faculte´ de Me´decine Paris Diderot Paris 7 and with the company Collin which is developing some activities in the domain of the head and neck (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 middle ear surgery. 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.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. 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, EVASION and ASCLEPIOS. The development program of the ADT started in 2007. After 3 years of development, more than 600,000 lines of code have been developed, 80,000 downloads of SOFA have been counted on the Inria gForge, and we are about to finalize a new version of the public release.

8.1.2. Sofa Intermeds, AEN

SOFA Large Scale Initiative on Medical Simulation (AEN): The variety and complexity of Medicine, as well as its ethical importance in today's society, have been a strong motivation in many scientific and technical disciplines. The medical field has already been a domain of application for computer science and several tools, such as image processing, are now an integral part of modern medicine. Yet, there is no question that the integration of new technologies in Medicine will continue to rise in the future. In this context, the simulation of medical procedures, whether it is targeted at education, planning of interventions, or even guidance during complex procedures, will be a major element of the Medicine of the twenty-first century. The main objective of this large scale initiative is to leverage expertise from a few research teams at Inria to speed up the development of new ideas, models, algorithms in this very multi-disciplinary field. This initiative started in 2008, and involves several teams at Inria: SHACRA, EVASION, ASCLEPIOS, MOAIS, MAGRIT, and BUNRAKU. This program has been evaluated by a group of international experts in October 2010.

8.1.3. 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.

8.1.4. 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. For this reason, Stephane Cotin has moved to Strasbourg for two years (Sept 2011 to July 2013).

8.1.5. 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.

8.2. International Research Visitors

8.2.1. Internships

Yiyi WEI (from Jan 2012 until Mar 2012)

Subject: Simulation of Coil Embolization using the Discrete Exterior Calculus Approach

Institution: Beihang University of Aeronautics and Astronautics (China)

9. Dissemination

9.1. Scientific Animation

9.1.1. Journals, Conferences, Workshop

- **Jérémie Dequidt** has been reviewer for the following conference and journal:
  - Medical Image Computing and Computer Assisted Intervention (MICCAI)
  - Transaction on Medical Imaging (TMI)
  - Computer Methods and Programs in Biomedicine (CMPB)
- **Christian Duriez** has been reviewer for the following conference and journals:
  - Computer Methods in Applied Mechanics and Engineering (CMAME),
  - Computer Methods and Programs in Biomedicine (CMPB),
  - IEEE Transaction on Medical Imaging (TMI),
  - IEEE Transactions on Biomedical Engineering (TBME-EMBS)
  - IEEE Transaction on Haptics (ToH),
  - Proceedings of IEEE,
  - Computer and Graphics,
  - Eurographics 2012,
  - Eurohaptics 2012,
  - Internaltional Conference on Control, Automation, Robotic and Vision (ICARCV 2012),
  - IEEE Virtual Reality Conference (VR 2012),
  - Medical Image Computing and Computer Assisted Intervention (MICCAI 2012)

  member of the following committees:
  - Associate Editor of WorldHaptic Conference 2013
- **Jérémie Allard** has been member of the following committees:
  - Workshop on Virtual Reality Interaction and Physical Simulation (VRIPHYS)

  and reviewer for the following conference and journal:
  - SIGGRAPH
  - Computers & Graphics

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Licence: Jeremie Dequidt, Programming, 48h, L3, Polytech'Lille, France
Licence: Jeremie Dequidt, Database, 12h, L3, Polytech'Lille, France
Licence: Jeremie Dequidt, Advanced Programming, 6h, L3, Polytech'Lille, France
Licence: Jeremie Dequidt, Hardware, 31h, L3, Polytech'Lille, France
Licence: Jeremie Dequidt, Unix Systems, 24h, L3, Polytech'Lille, France
Licence: Jeremie Dequidt, Numerical Analysis, 30h, L3, Polytech'Lille, France
Master: Jeremie Dequidt, 3D Modeling, 5h, M2, Polytech'Lille, France
Licence: Alexandre Bilger, Programming, 48h, L1, Université Lille 1, France
Master: Alexandre Bilger, Programming, 14h, L1, Polytech'Lille, France
Licence: Alexandre Bilger, Data Encoding, 32h, L1, Université Lille 1, France
Licence: Nazim Haouchine, Programming, 22h, L3, Polytech'Lille, France
Licence: Nazim Haouchine, Database, 36h, L3, Polytech'Lille, France
Licence: Ahmed Yureidini, Database, 32h, L1, Université de Lorraine, France
Licence: Ahmed Yureidini, Programming, 36h, L1, Université de Lorraine, France
Licence: Ahmed Yureidini, Hardware Architecture, 36h, L1, Université de Lorraine, France

9.2.2. Supervision

PhD & HdR :

PhD: **Yiyi Wei**, Discrete Exterior Calculus Approach for Aneurysm Related Simulation, USTL, 23/03/2012, **Stéphane Cotin and Songde Ma**

PhD in progress : **Ahmed Yureidini**, Modélisation d'organes par fonctions implicites, 2009, **Stéphane Cotin and Erwan Kerrien**

PhD in progress : **Hugo Talbot**, Real-time simulation of cardiac ablation in the framework of arrhythmia, 2010, **Stéphane Cotin and Hervé Delingette**

PhD in progress : **Vincent Majorczyk**, Simulation de Fluide GPU, 2010, **Stéphane Cotin and Jérémie Allard**

PhD in progress : **Guillaume Kazmitcheff**, Modélisation et simulation d'interventions chirurgicales sur l'oreille moyenne, 2011, **Stéphane Cotin and Christian Duriez**

PhD in progress : **Alexandre Bilger**, Biomecanical simulation for Deep Brain Stimulation, 2011, **Stéphane Cotin and Christian Duriez**

PhD in progress : **Zhifan Jiang**, Recalage d'images déformables pour la biomécanique, 2011, **Stéphane Cotin, Jérémie Dequidt, Mathias Brieu**

PhD in progress : **Tomas Golembiovsky**, Modèles déformables adaptatifs pour la simulation de structures creuses, 2011, **Stéphane Cotin, Ludek Matyska, Christian Duriez**

PhD in progress : **Julien Bosman**, Simulations à base de particules et interactions multi-physiques en temps-réel, 2011, **Stéphane Cotin and Christian Duriez**

PhD in progress : **Mouhamadou Diallo**,Modélisation biomécanique du prolapsus génital, 2011, **Mathias Brieu, Pauline Lecomte, Christian Duriez**

PhD in progress : **Nazim Haouchine**, Augmented Reality Tools for Minimally Invasive Hepatic Surgery, 2012, **Stéphane Cotin, Marie-Odile Berger, Jérémie Dequidt**

PhD in progress : **Francois Dervaux**, Image driven simulation for interventional radiology procedures, 2012, **Stéphane Cotin, Jérémie Dequidt, Erwan Kerrien**

9.2.3. Juries

- **Jérémie Allard** was in the examination committee of :
  - Guillaume Bousquet, October 2012, University of Grenoble

9.3. Popularization

During this year, team researchers and students animated several scientific events. The different scientific animations are listed below:

- MICCAI 2012: some of the team students helped for the organization of the MICCAI conference that occurred in October in Nice,
- Futur en Seine: a scientific exhibition took place in Paris (in the 104 building) the 16th and 17th June 2012 and was a public event. Researchers and students presented demonstration videos done using SOFA during the whole week-end.
- Recontre Inria-Industrie: this was a public event taking place in Strasbourg the 21st of November 2012. Researchers and students presented demonstration videos done using SOFA during the whole week-end.
- Hugo Talbot did a visit in the "Humanoids and Intelligence Systems" laboratory at the Karlsruhe Institute for Technology and presented his Ph.D. work at this occasion.
- Unithe ou Cafe: this is a vulgarization event at Inria presenting the research work done by Inria teams and is dedicated to all employees. Hugo Talbot presented his Ph.D. work during a session called "La cardiologie au coeur du numerique".

- Sofa Training Days Grenoble 2012: this is a 5 days-learning session held in october, with more than 20 attendees (researchers, ingeneers...). Various topics were presented by several members of the team.
- Some high school students have spent a week in the team and have been interested on topics related to Medical Simulation and in a large view to scientific researches.

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Major publications by the team in recent years

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Publications of the year

International Conferences with Proceedings

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