Activity Report 2011

# Team S.H.A.M.A.N

## Simulation in Healthcare for Advanced Medical ApplicatioNs

RESEARCH CENTER
**Lille - Nord Europe**

THEME
**Computational Medicine and Neurosciences**

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**Team S.H.A.M.A.N**

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

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# 2. Overall Objectives

## 2.1. Introduction

The SHAMAN 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 [35]. 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 [42]. 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 [33].

## 2.3. Highlights

- Two full papers have been accepted in the International Conference on Medical Image Computing and Computer Assisted Intervention (ERA's Ranking A).
- The team participated in the creation of the IHU of Strasbourg, an 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.

# 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 [29], [32] 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.

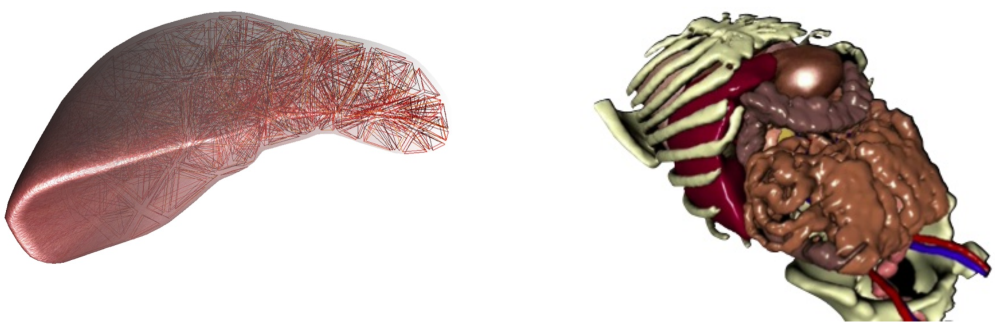

*Figure 1. Biomechanical models of organs, based on the Finite Element Method and elasticity theory. Left: a model of the liver based on tetrahedral elements and small strain elasticity. Right: several organ models from a patient dataset combined to create a realistic abdominal anatomy.*

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 [28]. 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.

### *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 [31]. 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. [36] 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. [38] 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.

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

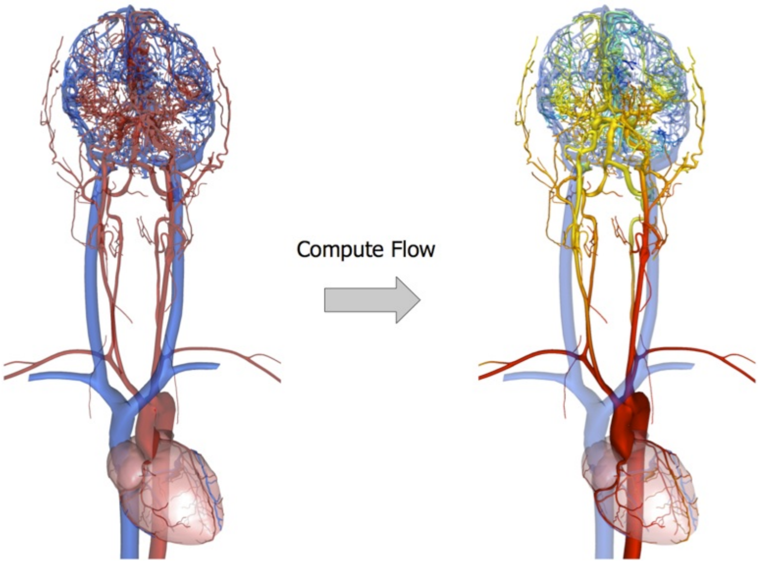


*Figure 2. Blood flow and pressure distribution in the cerebrovascular system. The arterial vascular network is composed of more than 3,000 vessels, yet the computation is performed in real-time.*

(blood vessel, aneurysm ventricle, ...) and combine it with some of our previous work describing laminar flow across a large number of vessels [43] 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 [33] and [34] 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 ( [37] 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] [33], [39], [26].

#### *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 [25]. The modeling of the intraocular implant and its deployment in the capsule has been published to the major conference in medical simulation [31].

#### *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 [34]. 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 [41], GiPSi [30], SPORE [40] or SSTML [27]. 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.

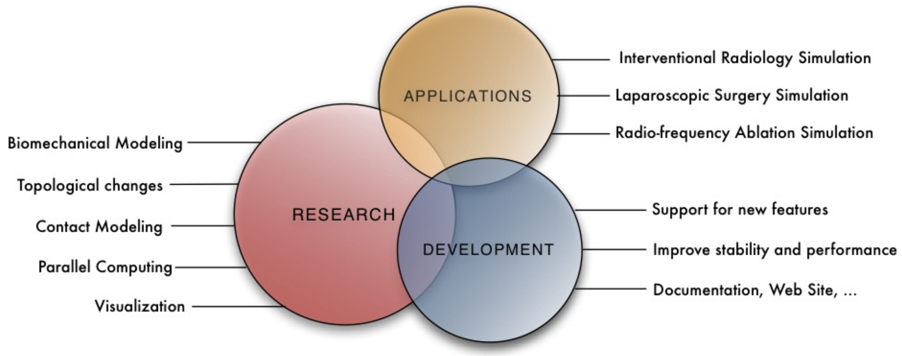


*Figure 3. Multidisciplinary research and development of the SOFA framework need to take place simultaneously to quickly advance research in the field of computer-based interactive medical simulation*

### 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. More than 87,000 downloads of SOFA have been counted as of December 2011. More than 70 researchers, students, engineers have contributed at various degrees to SOFA, for a total of about 700,000 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

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.

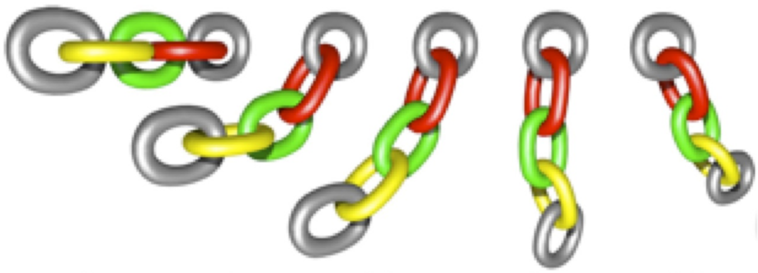

*Figure 4. Animation of a chain combining a FEM model, a mass-spring model, a FFD grid, and a rigid body. This example is a perfect illustration of the flexibility of SOFA. Not only several algorithms for rigid or deformable bodies can be part of the same simulation, but they can also interact in a physically 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*

# 6. New Results

## 6.1. Interactive Simulation of Liver Resection PASSPORT demonstration at SIGGRAPH

The 3-year EU PASSPORT project is being finalized. In this context, we created a GPU-based interactive simulation of laparoscopic liver resection that was selected for SIGGRAPH Real Time Live! [21]. While similar medical simulators have been developed in the past, this demonstration rely on advanced methods and the computational power of today GPUs to simulate multiple organs with high-resolution deformations and collisions in real-time. We use detailed meshes generated from segmented CT scans, facilitating the reproduction of patient-specific scenarios, as is necessary for the pre-operative rehearsal of complex or risky medical cases. In the presented application, the user can examine the mechanical and collision models, and the generated contacts while the simulated patient is breathing. He can manipulate a laparoscopic instrument to navigate through the abdominal cavity, push on organs and perform a thermal ablation.

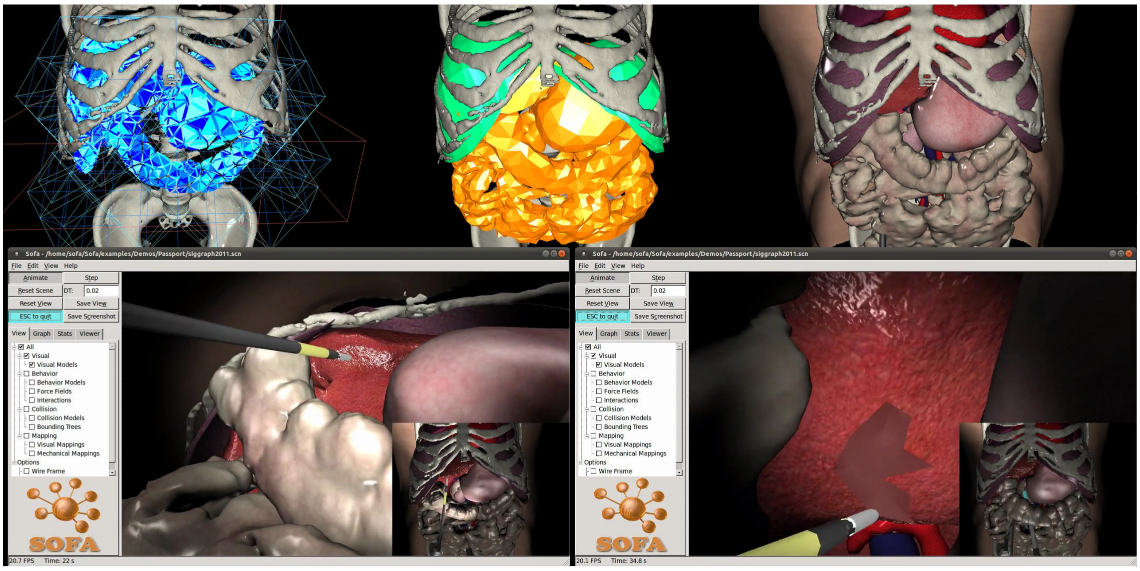

*Figure 5. Left: mechanical FEM models (4k tetrahedra), Middle: Collision surfaces (15k triangles), Right: Visual Models. Bottom: the user view during liver resection. The resulting simulation runs at 25 FPS.*

While similar medical simulators have been developed in the past 10 years, this demonstration is based on recently proposed methods: high-resolution Finite Element Model (FEM) with implicit time-integration implemented on GPU [1], volume contact constraints [2], an efficient numerical solver based on asynchronous preconditioning [17], as well as improvements in visual and haptic rendering. These methods allow to simulate in real-time all organs in the abdominal cavity using a improved level of precision compared to previous works. The FEM formulation enables to reproduce specific material properties. Contacts are handled by precise constraints with frictions on detailed surface meshes. Both methods support topological changes efficiently, as demonstrated by performing a resection of a portion of a liver, an important step in surgical procedures performed to remove cancerous tumors. This work was presented at SIGGRAPH 2011 [21].

## 6.2. Biomechanical simulation of electrode migration for deep brain stimulation

Deep Brain Stimulation is a modern surgical technique for treating patients who suffer from affective or motion disorders such as Parkinson's disease. The efficiency of the procedure relies heavily on the accuracy of the placement of a micro-electrode which sends electrical pulses to a specific part of the brain that controls motion and affective symptoms. However, targeting this small anatomical structure is rendered difficult due to a series of brain shifts that take place during and after the procedure. We introduce a biomechanical simulation of the intra and postoperative stages of the procedure in order to determine lead deformation and electrode migration due to brain shift. To achieve this goal, we propose a global approach, which accounts for brain deformation but also for the numerous interactions that take place during the procedure (contacts between the brain and the inner part of the skull and falx cerebri, effect of the cerebrospinal fluid, and biomechanical interactions between the brain and the electrodes and cannula used during the procedure). Preliminary results show a good correlation between our simulations and various results reported in the literature. This work was presented at MICCAI 2011 [16].

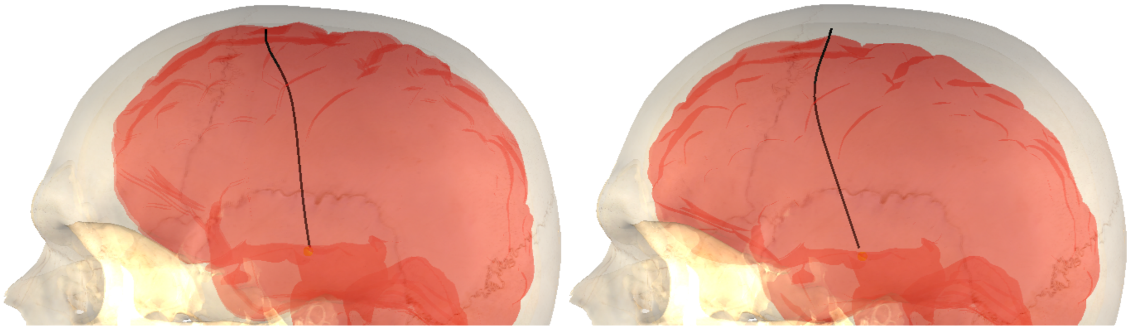

*Figure 6. Screenshot showing the simulated deflection of the right electrode immediately after operation (left) and several weeks after the operation (right).*

## 6.3. Preconditioner-Based Contact Response and Application to Cataract Surgery

We introduced a new method to compute, in real- time, the physical behavior of several colliding soft-tissues in a surgical simulation. The numerical approach is based on finite element modeling and allows for a fast update of a large number of tetrahedral elements. The speed-up is obtained by the use of a specific preconditioner that is updated at low frequency. The preconditioning enables an optimized computation of both large deformations and precise contact response. Moreover, homogeneous and inhomogeneous tissues are simulated with the same accuracy. This method was used in a simulation of one step in a cataract surgery procedure, which require to handle contacts with non homogeneous objects precisely. This work was presented at MICCAI 2011 [17].

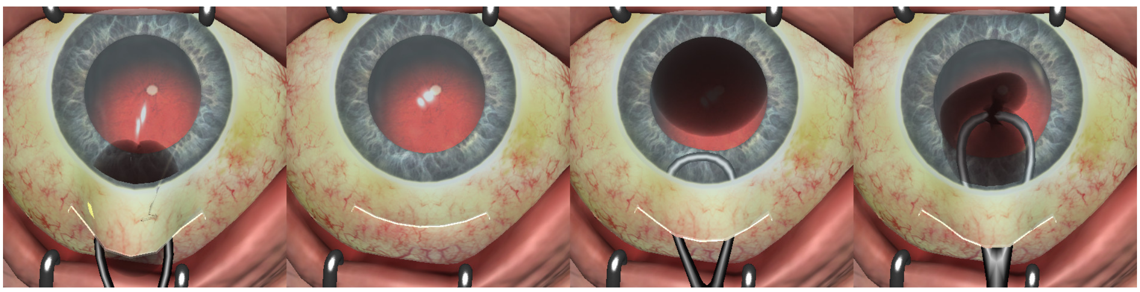

*Figure 7. Simulation of the extraction of the eye lens during Manual Small Incision Cataract Surgery (MSICS).*

## 6.4. Interactive Blood-Coil Simulation in Real-time during Aneurysm Embolization

We introduced a complete process for patient-specific simulations of coil embolization, from mesh generation with medical datasets to computation of coil-flow bilateral influence. We propose a new method for simulating the complex blood flow patterns that take place within the aneurysm, and for simulating the interaction of coils with this flow. Porous media was introduced to model the impact of the coil onto the flow (as a change of flow pattern and a decrease of velocity) from a statistical point of view, while the reverse effect on the coil (as a shift in the blood flow) was described by the local drag force. By solving the Navier-Stokes Equations with extra porous terms using the DEC method, the velocity field of blood flow was obtained, and then used to compute the drag force applied on the coil during aneurysm embolization. This work was published in the Computers & Graphics journal [13].

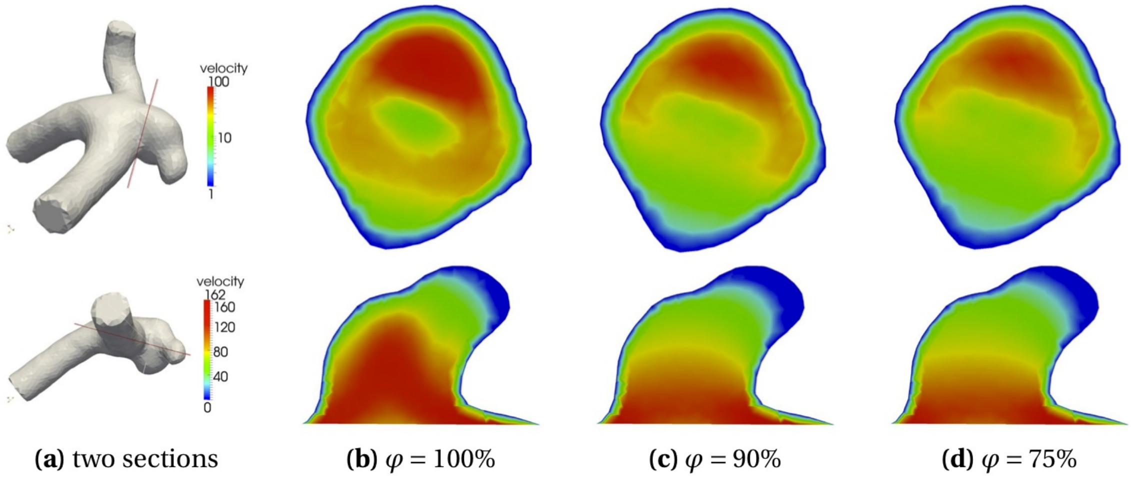


*Figure 8. Coil embolization: the simulated blood flow velocity magnitude on (a) two sections (b) before the embolization, (c) after the first coil deployed, (d) after the final coil.*

## 6.5. Constraint-based Haptic Rendering of Multirate Compliant Mechanisms

The research, that is published in IEEE transaction of Haptics [12], is dedicated to haptic rendering of complex physics-based environment in the context of surgical simulation. A new unified formalism for modeling the mechanical interactions between medical devices and anatomical structures and for computing accurately the haptic force feedback is presented. The approach deals with the mechanical interactions using appropriate force and/or motion transmission models named *compliant mechanisms*. These mechanisms are formulated as a constraint-based problem that is solved in two separate threads running at different frequencies. The first thread processes the whole simulation including the soft-tissue deformations, whereas the second one only deals with computer haptics. This method builds a bridge between the so called virtual mechanisms (that were proposed for haptic rendering of rigid bodies) and intermediate representations (used for rendering of complex simulations). With this approach, it is possible to describe the specific behavior of various medical devices while relying on a unified method for solving the mechanical interactions between deformable objects and haptic rendering. The technique is demonstrated in interactive simulation of flexible needle insertion through soft anatomical structures with force feedback.

## 6.6. Asynchronous Haptic Simulation of Contacting Deformable Objects with Variable Stiffness

This research, published in IROS proceedings [18] presents a new asynchronous approach for haptic rendering of deformable objects. When stiff non-linear deformations take place, they introduce important and rapid variations of the force sent to the user. This problem is similar to the stiff virtual wall for which a high

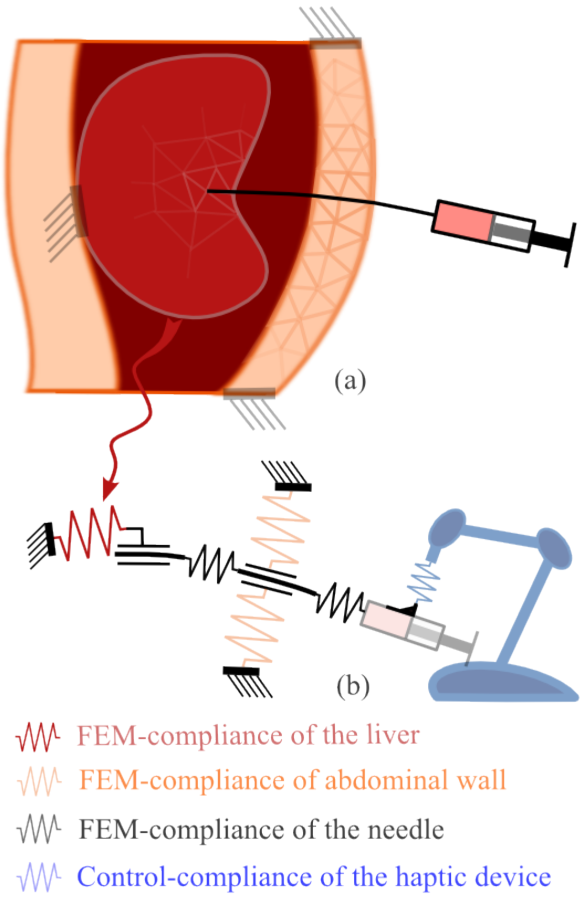


*Figure 9. Constraint-based Haptic Rendering of Multirate Compliant Mechanisms*

refresh rate is required to obtain a stable haptic feedback. However, when dealing with several interacting deformable objects, it is usually impossible to simulate all objects at high rates. To address this problem we propose a quasi-static framework that allows for stable interactions of asynchronously computed deformable objects. In the proposed approach, a deformable object can be computed at high refresh rates, while the remaining deformable virtual objects remain computed at low refresh rates. Moreover, contacts and other constraints between the different objects of the virtual environment are accurately solved using a shared Linear Complementarity Problem (LCP). Finally, we demonstrate our method on two test cases: a snap-in example involving non-linear deformations and a virtual thread interacting with a deformable object.

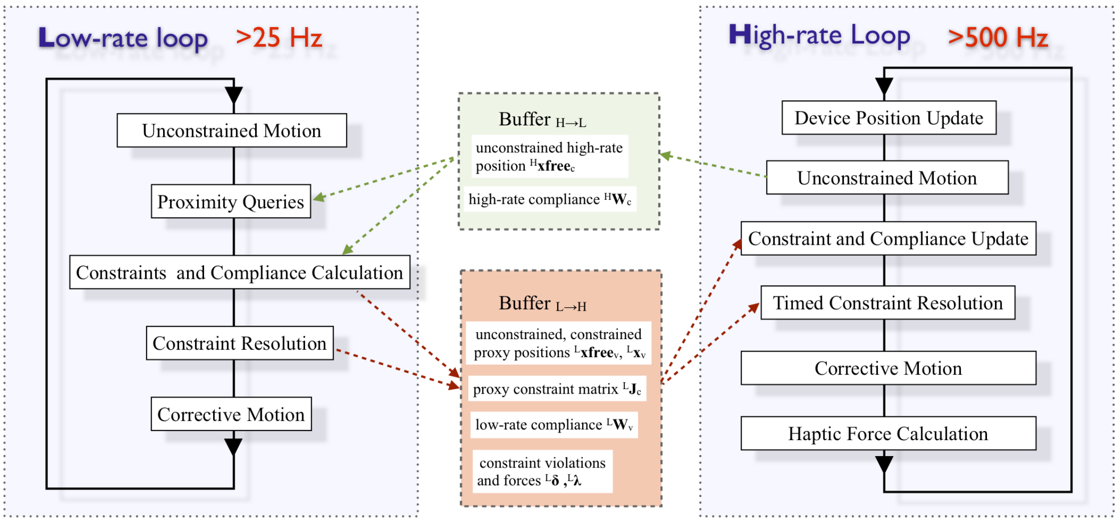


*Figure 10. Schematic visualization of the computational model*

# 7. Contracts and Grants with Industry

## 7.1. Contracts with Industry

### *7.1.1. 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.

### *7.1.2. Collin*

We have started a collaboration with INSERM - UMR-S 867 ( robot based minimally invasive otologic surgery) Faculté de Médecine Paris Diderot Paris 7 and with the company Collin which is developing some activities in the domain of the head and neck (implants, surgery 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 Kazmicheff 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, SHAMAN, 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: SHAMAN, 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 one year (Sept 2011 to July 2012).

## 8.2. European Initiatives

### *8.2.1. Collaborations in European Programs*

Program: FP7

Project acronym: PASSPORT

Project title: PAtient Specific Simulation and PreOperative Realistic Training for liver surgery

Duration: May 2008 - November 2011

Coordinator: IRCAD

Other partners: ETH, Computer Vision Laboratory (Switzerland), Technische Universität München, Computer-Aided Medical Procedures (Germany), Imperial College London (UK), Inserm (France), Storz (Germany), Université de Strasbourg (France), Universität Leipzig, Interdisciplinary Centre for Bioinformatics (Germany),

Abstract: PASSPORT (PAtient Specific Simulation and PreOperative Realistic Training for liver surgery), is a 3-year project that deals directly with the objectives of the "Virtual Physiological Human" ICT-2007.5.3 objective. Indeed, PASSPORT's aim is to develop patient-specific models of the liver which integrates anatomical, functional, mechanical, appearance, and biological modeling. To these static models, PASSPORT will add dynamics liver deformation modeling and deformation due to breathing, and regeneration modeling providing a patient specific minimal safety standardized FLR. These models, integrated in the Open Source framework SOFA, will culminate in generating the first multi-level and dynamic "Virtual patient-specific liver" allowing not only to accurately predict feasibility, results and the success rate of a surgical intervention, but also to improve surgeons' training via a fully realistic simulator, thus directly impacting upon definitive patient recovery suffering from liver diseases.

# 9. Dissemination

## 9.1. Animation of the scientific community

### *9.1.1. Examination Committees*

- **Christian Duriez** was reviewer for 2 ANR Projects (TECSAN and SAGA calls)

### *9.1.2. Journals, Conferences, Workshop*

- **Stéphane Cotin** has been reviewer for the following conferences and journals :
  - Medical Image Computing and Computer Assisted Intervention (MICCAI)
  - Transaction on Medical Imaging (TMI)
  - Revue Electronique Francophone d'Informatique Graphique (REFIG)
  - IEEE Transaction on Haptics (ToH)
- **Jérémie Dequidt** has been reviewer for the following conference and journal:
  - Medical Image Computing and Computer Assisted Intervention (MICCAI)
  - Transaction on Medical Imaging (TMI)
- **Christian Duriez** has been reviewer for the following conference and journals (this year):
  - 3DUI 2011, IROS 2011, JVRC2011, MICCAI 2011 (5 papers), WorldHaptic 2011, Eurographics 2012, IEEE VR 2012

- – IEEE Transaction on Visualization and Computer Graphics (TVCG), IEEE Transaction on Haptics (ToH)
- **Jérémie Allard** has been member of the following committees:
  - – 8th Workshop on Virtual Reality Interaction and Physical Simulation – VRIPHYS 2011
  - – Displays for the Near Future Symposium - LAVAL 2011

  and reviewer for the following conferences and journal:
  - – SIGGRAPH
  - – Motion in Games (MIG)
  - – Computers & Graphics journal.

### *9.1.3. Scientific and Administrative Responsibilities*

- **Christian Duriez** is involved in the organization of the colloquium POLARIS for scientists in computer-science and automation in Lille (http://www.colloquiumpolaris.fr/)
- **Stéphane Cotin** is vice-president of the CDT (Commission des Développements Technologiques) at Inria
- **Jérémie Dequidt** was a member of the Computers Users Committee (CUMI) of Inria Lille

## 9.2. Teaching

Permanent members teach the following courses:

- **Jérémie Dequidt** heads the *Communicating Systems* track at Polytech'Lille engineering school where he teaches several courses on Computer Graphics, High Performance Computing, Numerical Analysis and Software Engineering.
- **Christian Duriez** teaches courses on finite element method at ICAM (Institut Catholique d'Arts et Métiers) in Lille (about 64h courses)
- **Shaman Team** teaches courses about medical simulation in the Master IVI (8h courses/ 8h tutorials)

PhD & HdR :

PhD : **Hadrien Courtecuisse**, Nouvelles architectures parallèles pour simulations interactives médicales, USTL, 12/09/2011, **Stéphane Cotin, Jérémie Allard, Christian Duriez** [11]

PhD in progress : **Yiyi Wei**, Discrete Exterior Calculus Approach for Aneurysm Related Simulation, 2008, **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 interne, 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 Leconte, Christian Duriez**

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### Doctoral Dissertations and Habilitation Theses

[11] H. COURTECUISSE. *Nouvelles architectures parallèles pour simulations interactives médicales*, Université des Sciences et Technologies de Lille, December 2011.

## Articles in International Peer-Reviewed Journal

[12] I. PETERLÍK, M. NOUICER, C. DURIEZ, S. COTIN, A. KHEDDAR. *Constraint-Based Haptic Rendering of Multirate Compliant Mechanisms*, in "IEEE Transactions on Haptics", 2011, vol. 4, p. 175-187, http://doi.ieeecomputersociety.org/10.1109/TOH.2011.41.

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