Surgery Simulation

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Abstract

The purpose of surgery simulation is twofold. First, these simulators allow to train surgeons at performing complex surgical gestures such as video-surgery (endoscopy, laparoscopy,...) with a greater flexibility than existing training techniques. Second, such simulators may contribute to plan with a greater accuracy, complex surgical procedures or even may be used to conceive completely new procedures.

The building of surgical simulators raises several important technical and scientific issues. For instance, the issue of modeling mathematicallty the physics and physiology of the human body remains largely unexplored.

Furthermore, real-time computation is an important constraint for these simulators. Indeed, it is mandatory for the simulation effectiveness that the user is completely immersed inside the virtual surgical environment created in the simulator. For a correct visual feedback, a refreshment rate of 30 Hz is for instance necessary. Combining a realistic modeling of the surgical field with a computationally efficient implementation is one of the main challenges of surgery simulation.

1 Surgery Simulation

1.1 Medical Impact

Surgery simulation aims at reproducing the visual and haptic senses experienced by a surgeon during a surgical procedure, through the use of computer and robotics systems. The medical interest of this technology is linked with the development of minimally invasive techniques especially video-surgery (endoscopy, laparoscopy,...). More precisely, laparoscopy consists in performing surgery by introducing different surgical instruments in the patient abdomen through one centimeter-wide incisions. The surgeon can see the abdominal anatomy with great clarity by watching a high resolution monitor connected to an endoscope introduced inside the patient abdomen. This technique bears several advantages over traditional open surgery. On one hand, it decreases the trauma entailed by the surgical procedure on the patient body. This allows to decrease the patient stay in hospitals and therefore decrease the cost of health care. On the other hand, it reduces the morbidity as demonstrated by the Hunter and Sackier study [HJ94].

However, if these minimally invasive techniques are clearly beneficial to the patients, they also bring new constraints on the surgical practice. First, they significantly degrade the surgeon access to the patient body. In laparoscopy for instance, the surgical procedure is made more complex by the limited number of degrees of freedom of each surgical instruments. Indeed, they must go through fixed points where the incisions in the patient abdomen has been done. Furthermore, because the surgeon cannot see his hand on the monitor, this technique requires a specific hand-eye coordination. Therefore, an important training period is required before a surgeon acquires the skills necessary to adequately perform minimally invasive surgery.

Currently, surgeons are trained to perform minimally invasive surgery by using mechanical simulators or living animals. The former method is based on “endotrainers” representing an abdominal cavity inside which are placed plastic objects representing human organs. These systems are sufficient for acquiring basic surgical skills but are not realistic enough to represent the complexity of the human anatomy (respiratory motion, bleeding,...). The latter training method consists in practicing simple or complex surgical procedures on living animals (often pigs). This method has two limitations. First, the similarity between the human and pig anatomy is limited and therefore certain procedures cannot be precisely simulated with this technique. Also, the evolution of the ethical code in most countries may forbid the use of animals for this specific training, as it already the case in different European countries.

Because of the limitations of current training methods, there is a large interest in developing video-surgery simulation software for providing efficient and quantitative gesture training systems. Indeed, such systems should bring a greater flexibility by providing scenarios including different types of pathologies. Furthermore, thanks to the development of medical image reconstruction algorithms, surgery simulation allows surgeon to verify and optimize the surgical strategy of a procedure on a given patient.

1.2 Surgical Simulators

Satava *et al.* [Sat96] have proposed to classify surgical simulators into three categories (see figure (1)). The first generation simulators are solely based on anatomical information, in particular on the geometry of the anatomical structures included in the simulator. In these simulators, the user can virtually navigate inside the human body but has a limited interaction with the modeled organs. Currently, several first generation surgical simulators are available including commercial products linked to medical imaging systems (CT or MRI scanners) that are focusing on virtual endoscopy (colonoscopy, tracheoscopy,...). In general, they are used as a complementary examination for establishing a diagnosis (for instance when using virtual endoscopy) or as a surgical planning tool before performing surgery.

In addition to geometrical information, second generation simulators describe the physical properties of the human body. For instance, the modeling of soft tissue biomechanical properties enables the simulation of basic surgical gestures such as cutting or suturing. Currently, several prototypes of second generation simulators are being developed including the simulation of cholecystectomy [CEO93, KKKN96], of arthroscopy of the knee [GSMF97] and of gynecological surgery [SMB99]. Section 3 will shortly described the hepatic surgery simulator being developed at INRIA.

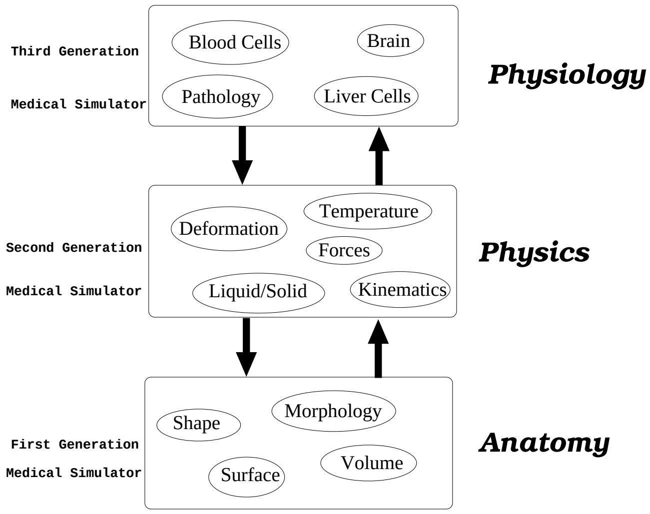


Figure 1: The different generations of medical simulators.

Third generation of surgical simulators provide an anatomical, physical and physiological description of the human body. There are very few simulators including these three levels of modeling, essentially because of the difficulty to realistically describe the coupling between physiology and physics. A good example of such simulators is given by the work of Kaye *et al.* [JK97] who have modeled the mechanical cardiopulmonary interactions.

2 General Issues in Surgery Simulation

2.1 Simulator Architecture

We are now focusing on the creation of simulators for surgical gesture training and especially in the context of minimally invasive therapy. For the acquisition of basic skills, it is necessary to simulate the existence of "living" tissues and therefore to develop a second generation surgical simulator. However, the development of such simulators raises important technical and scientific issues. The different components of these simulators are summarized in figure (2).

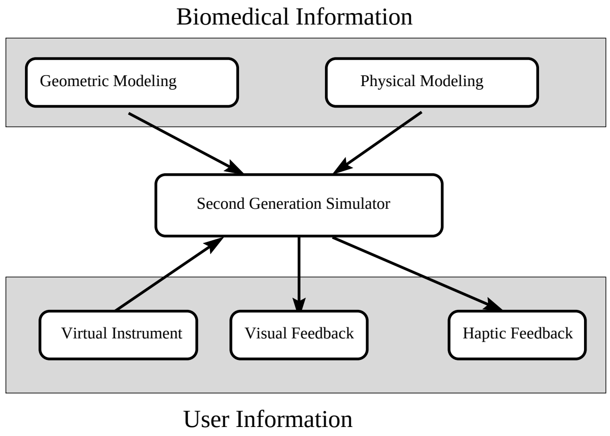


Figure 2: The different components of a second generation surgery simulator.

First, it is necessary to model the geometry and physics of the anatomical structures described in the simulation. Furthermore, the simulator must provide an advanced user interface including visual and force feedback. This interface can be decomposed into three distinct modules. The first module must model the physical interaction between surgical instruments and virtual organs. In particular, this task includes the collision detection and the collision processing that occur during the simulation. The second module aims at displaying the operating field on a video monitor in the most realistic manner. The third module must control a force-feedback device so that the user can feel the applied forces when the virtual instrument is in contact with an anatomical structure. In the reminder of this section, we describe in more details the five components of a second generation medical simulator.

2.2 Geometric Modeling

The extraction of tridimensional geometric models of anatomical structures are in general based on medical imagery: CT scanner images, MRI images, cryogenic images, 3D ultrasound images,... Because medical images resolution and contrast have greatly improved over the past few years, the tridimensional reconstruction of certain structures have become possible by using computerized tools. For instance, the availability in 1995 of the “Visible Human” dataset by the National Library of Medicine has allowed the creation of a complete geometric human model [Ack98]. However, the automatic delineation of structures from medical images is still considered as an unsolved problem. Therefore a lot of human interaction are usually required for the tridimensional reconstruction of the human anatomy. In [Aya98], Ayache provides a survey on medical image analysis.

2.3 Physical Modeling

In a second generation surgical simulator, it is especially important to focus on the mechanical properties of anatomical structures. The field of biomechanics characterizes at microscopic and macroscopic levels the behavior of biological tissues. In general, this behavior is very complex with phenomenon of non-linearity, hysteresis, plasticity and fatigue. In fact, only a small number of tissue types have been studied extensively like the skin and muscles. A tissue behavior may be characterized by the stress-strain relationship obtained after a rheological experiment.

Several mathematical models [MWT98] have been proposed to represent most common behaviors. In general, these models are based on the theory of continuum mechanics. However, in order to use these models in a surgical simulator, it is required to simplify and optimize their computer implementation. A survey on soft tissue modeling can be found [Del98].

2.4 Virtual Instrument Interaction

A key part of a surgery simulation software is the user interface. The hardware interface to drive the virtual instrument essentially consists in one or several force-feedback systems having the same degrees of freedom and appearance than actual surgical instruments used in minimally invasive therapy (see figure (3)). In general, these systems are force-controlled, sending the instrument position to the simulation software and receiving force targets.

Once the position of the virtual instrument is known, it is necessary to detect possible collisions with other instruments or surrounding anatomical structures. In this case, it is particularly difficult to obtain a computationally efficient collision detection algorithm because the geometry of objects may change at each iteration. Therefore, algorithms based on pre-computed data structures (such as the approach proposed in [GLM96]) are not appropriate. In [LCN99], Lombardo *et al.* proposed an original collision detection method based on the OpenGL graphics library that is especially well-suited for instruments shaped like sticks. When a collision is detected, a set of geometrical or physical constraints are applied on soft tissue models. However, modeling the physics of contacts can lead to complex algorithms and therefore purely geometric approaches are often preferred.

Figure 3: A force feedback system suited for surgery simulation (courtesy of Immersion Corporation www.immerse.com)

2.5 Visual Feedback

In order to succeed in training surgeon, a simulator must provide a realistic visual representation of the surgical procedure. Visual feedback is especially important in video-surgery because it helps the surgeon in acquiring a tridimensional perception of his environment. In particular, the effects of shading, shadows and textures are important clues that must be reproduced in a simulator.

Two main techniques may be used to produce these effects: surface rendering or volume rendering. A comparison between these two rendering techniques for surgery simulation is described in [ZS98]. The quality of visual feedback is directly related to the availability and performance of graphics accelerators. Despite the fast development and improved price-performance ratio of graphics boards on workstations, the realistic simulation of effects such as blood flow still require an amount of graphics and computation resources than is not available on current computers.

2.6 Haptic feedback

The sense of touch experienced by a surgeon when manipulating a surgical instrument is also an important clue for the tridimensional understanding of the surgical gesture. However, the small speed at which instruments are displaced, and also the instruments friction with trocards limit the direct perception of the surgeon. In fact, it appears that it is the coupling between visual feedback and force feedback that produce the sense of immersion. In [Mar96], it is demonstrated that the use of a force-feedback device positively contribute to the evaluation of a surgical simulator.

Haptic feedback requires a greater bandwidth than visual feedback. The typical refresh rate necessary for a satisfactory visual feedback is estimated to be 30 Hz. For force feedback this frequency is dependent on the deformable nature of the simulated material. Thus, for simulating the contact with a soft object, a refresh rate of 300 Hz should be sufficient whereas for hard object a refresh rate greater than 1000 Hz should be used. The problem of force-feedback for surgery simulation is debated in [EC98].

2.7 Implementation of a simulator

Most of the difficulties when implementing a surgical simulator originates from the trade-off between real-time interaction and the necessary surgical realism of a simulator.

The first constraint indicates that there must be a minimum bandwidth between the computer and the interface devices in order to provide a satisfactory visual and haptic feedback. If this bandwidth is too small, the user cannot properly interact with the simulator and it becomes useless for surgery gesture training. However, the word “real-time” can be interpreted in different ways. Most of the time, it implies that the mean refresh rate is high enough to allow a suitable interaction. However, it is possible that during the simulation, some events (such as the collision with a new structure) may increase the computational load of the machine. This may result in a lack of synchronicity between the user gesture and the user perception from the simulator. Even, when the computation time is too irregular, the user may not be able to use the simulator. In order to guarantee a good user interaction, it is necessary to use a dedicated “real-time” software that supervises all existing tasks being run on the simulator.

The second constraint is related to the goal of a simulator : training surgeons to new gestures or procedures. To reach this goal, the user must “believe” that the simulator environment corresponds to a real procedure. The level of realism of a simulator is therefore very dependent on the type of surgical procedures and is also connected with physio-psychological parameters. In any case, increasing the realism of a simulator requires an increase of computational time which is contradictory with the constraint of real-time interaction.

The main difficulty in implementing a simulator is to optimize the simulator credibility for a given amount of graphics and computational resources. For instance, an analysis of the training scenario should be done to find the most important elements that contribute to the simulation realism. Also, algorithms for soft tissue modeling and user interaction are the most critical modules for achieving real time computation. Therefore, it is important to optimize their performance but also their functionality.

3 INRIA Hepatic Surgery Simulator

The collection of articles attached to this paper covers some aspects of the research done at INRIA for developing an hepatic surgery simulator. This work has been initiated during the European project MASTER by the Epidaure project of INRIA in collaboration with the IRCAD research center[1] where the European Institute of Tele-Surgery (EITS) is located. The development of an hepatic surgery simulator was proposed by Pr J. Marescaux in 1995 because of the medical importance of hepatic pathologies and because of the relative complexity of hepatic surgery. This work has also benefited from the INRIA incentive action AISIM[2] that has gathered different INRIA teams working in the fields of medical image analysis (Epidaure), robotics (Sharp), computer graphics (Imagis) and numerical analysis (Sinus, Macs).

In the next sections, we summarize the different aspects of this hepatic surgery simulator.

3.1 Tridimensional Liver Reconstruction

In a first stage, a set of computerized tools have been developed to extract different structures from abdominal CT scan images as shown in figure (4) : liver envelope, portal and sus-hepatic venous trees, the eight Couinaud segments and hepatic lesions. This reconstruction is performed in three distinct steps. First, the liver is delineated from the CT scan image and then venous trees and hepatic lesions are extracted. Finally the eight Couinaud segments are reconstructed based on the portal vein geometry and topology.

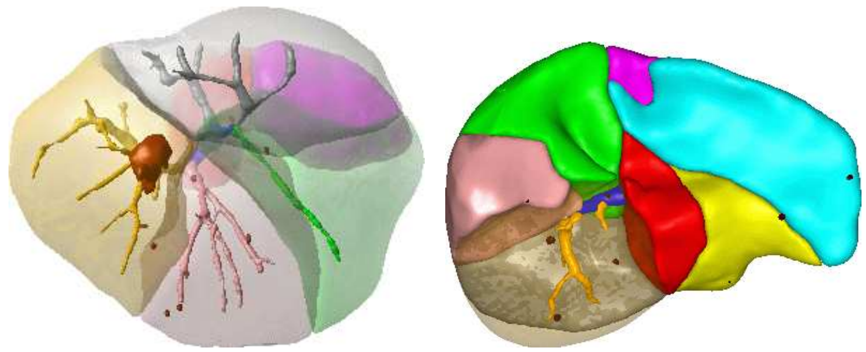
The liver extraction step is based on a deformable surface mesh, called "simplex mesh" (whose general properties are described in [Del99]). This mesh is embedded in the abdominal CT-scan image and then deformed in order to fit the liver outlines in the image. The mesh has an a priori knowledge about its shape and uses this shape information during the deformation process to improve the delineation robustness. The algorithm used to control the mesh deformation is described in [MD98]. The geometric reconstruction of liver anatomy has been primarily utilized for the planning of hepatic surgery. In [MCTK98], Pr. Marescaux describes the impact and the expected outcomes of this work on the clinical practice of hepatic surgeons.

3.2 Physical Modeling

Soft tissue modeling is a task requiring a lot of computational resources. We have focused in developing new algorithms for computing realistic tissue deformation in the most efficient manner. Our approach is based on the theory of continuum mechanics et more precisely on the theory of linear elastiity. Indeed, linear elasticity is a physical model which is valid for small displacements and small deformations. Furthermore, in order to guarantee the spatial

[1]Institut de Recherche Contre le Cancer de l'Appareil Digestif, 1, Place de l'Hôpital, 67091 STRASBOURG Cedex, http://www.ircad.com/

[2]http://www-sop.inria.fr/epidaure/AISIM/



(a) (b)

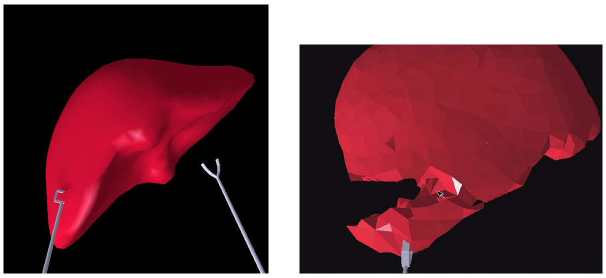
Figure 4: Liver reconstructions from abdominal CT scan images.

continuity of deformations, we use the finite element method for the discretization of all physical models. This approach differs from the commonly used spring-mass models that do not take into account the material continuity.

We present two complementary algorithms for soft tissue deformation. The former method pre-computes the possible deformations of a linear elastic model and uses the superposition principle to compute in a very efficient manner the model deformation during a collision with one or several surgical instruments. This algorithm is presented more precisely in [CDA99]. However, because of the pre-computation stage, this method has one major limitation : it does not allow the simulation of cutting or suturing. The latter algorithm introduces a new dynamic model having the same computational complexity than spring-mass models, but having a linear elastic behavior. Because of its similarity with spring-mass models we have called these models "tensor-mass" models. Figure (5) shows two examples of soft tissue deformation based on a pre-computed and a tensor-mass model.

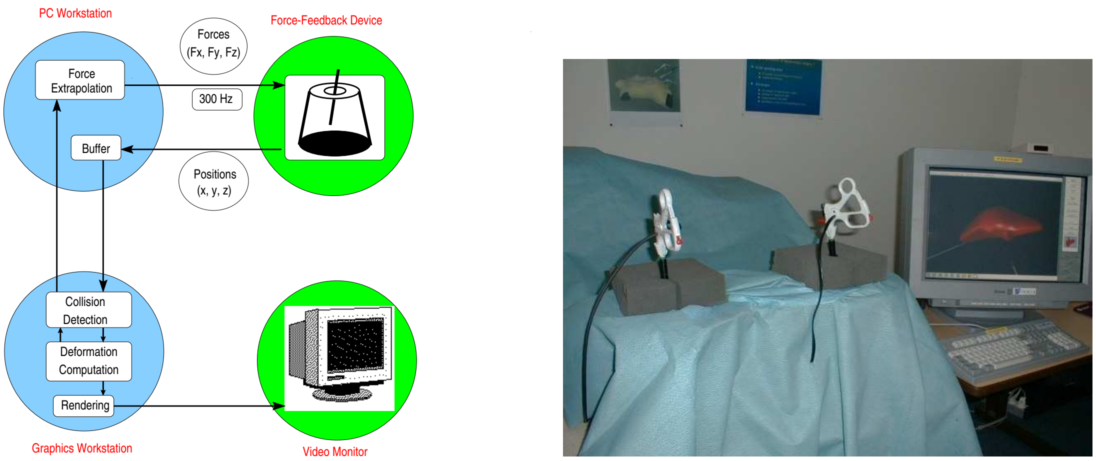
3.3 Simulator Overview

The software and hardware architecture of the simulator is presented in figure (6-a). Most of the computation are performed on a graphics workstation (a Onyx2 InfiniteReality or Linux PC workstation) that also displays the surgical field on its video monitor. The force-feedback systems are connected to a PC workstation that communicates through an ethernet link with the graphics workstation. A software for extrapolating forces sent to the force-feedback system has been implemented in order to increase the bandwidth of the haptic feedback (see [PL99]) for more details.



(a) (b)

Figure 5: (a) Liver deformation computed on a precomputed linear elastic model; (b) Cutting operation on a liver represented with a tensor-mass model.



(a) (b)

Figure 6: (a) Hepatic surgery simulator; (b) View of the simulator.

4 Conclusion

In this article we have described the key technologies for building a second generation surgery simulator. It is important to note than these technologies cover a large range of scientific fields including the domains of medicine, medical image analysis, biomechanics, numerical analysis, computer graphics and robotics. Among the key problems that should be addressed, soft tissue modeling, realistic visual rendering and the modeling of contact with instruments are of specific importance. The outcomes of these technologies should have an impact in other medical applications (surgery planning, image segmentation, prediction of pathology evolution,..) but also may have contribute to the development of new methodologies in the field of structural mechanics or biomedical engineering.

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