Volumetric Deformable Models for Simulation of Laparoscopic Surgery

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Abstract

In this paper we present a method for solving both problems of force feedback and real time deformations of virtual organs, especially needed for surgical simulators. Our method is based on the linear elasticity theory with a preprocessing algorithm which entails real time performances. We have applied this technique to a liver model derived from a complete anatomical representation.

1 INTRODUCTION

Minimally invasive surgical techniques offer surgeons a new perspective in the way operative procedures are performed. Although they can adapt to most of the differences with standard surgery (eye-hand coordination, 2D vision, etc.), it seems that an efficient training on a simulator could greatly enhance the control of surgical procedures. Nevertheless, whatever the quality of the simulation, an apprenticeship on animals or humans will probably remain unavoidable for years. That is the reason why we only focus on a simulator for gesture training, where a surgical procedure is broken down into a set of basic actions. Thanks to simulators, each task can be repeated a great number of times, recorded for later use, measured according to efficiency criteria, etc. Moreover, particular tumors or pathologies, that would rarely occur in reality, can be easily introduced into the model of the organ. According to these requirements, this project of simulator, developed in collaboration with surgeons and anatomists of IRCAD, has emerged on two related applications. First, we have created a very accurate model of the liver, including all the vascularization and the gall-bladder, that can be used for anatomical studies. Second, this model has been simplified into a volumetric deformable mesh having attractive properties for real time simulation of laparoscopic surgery.

2 LAPAROSCOPIC SURGERY SIMULATION

A realistic simulation of surgery implies several constraints in terms of geometric modeling, laws of deformation and force feedback. First of all, a very accurate model of the target organ is required. For anatomical teaching, a generic model is sufficient whereas patient-based models are needed for surgical planning or simulation.

2.1 Anatomical model of the liver

Advanced medical imaging techniques developed in the Epidaure group allow us to build three dimensional models of organs from various image modalities. For anatomical study, each detail is of importance while most of the actual imaging techniques do not permit such precision without risks for the patient (due to the importance of the acquisition time). Therefore, we have constructed a model of the liver from the NLM Visible Human Database. This database is a volumetric color description of the anatomy of an entire male cadaver with $\frac{1}{3} \times \frac{1}{3} \times 1$ millimeter voxels. The reconstructed liver is represented with anatomical details including soft tissues, the four vascular trees of distribution and the gall-bladder (fig. 1). The choice for a specific geometric representation of anatomical parts is of prime importance and should be governed by the resulting trade-off between realism and interaction [2]. Three dimensional active contours [3] have been used for segmenting the volumetric image and extracting a geometric representation (*simplex mesh*) of the surface. This mesh is easily refined in regions of high curvature for an optimal representation (precision *vs* number of vertices) of the surface. This simplex mesh has also the property to be easily transformed in a triangulation and, by extension, in a tetrahedrization of the volume delimited by this surface. This decomposition of the volume in a set of tetrahedrons will be used in the following for the resolution of the elasticity problem with a finite element method.

2.2 Volumetric deformations and force feedback

Since a simulator of laparoscopic surgery should take into account the elastic nature of the tissues, the relevance of our model is related to its ability to reproduce the behaviour of a real organ under some specific constraints. Moreover, the realism of the simulation is enhanced when volumetric deformations and force feedback can be performed [5] [9]. In our system, the sensation of forces is coupled with the elastic nature of the virtual organ. This relation is important to generate forces in relation with the anatomical characteristics of the organ by a variation of the stiffness according to the nature of the tissues.

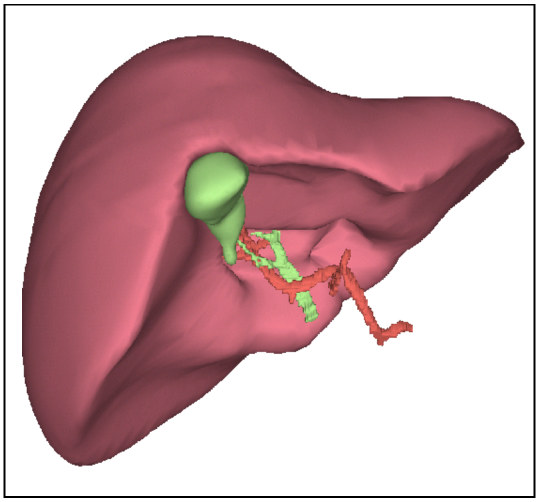

Figure 1-a
Opaque representation
This representation corresponds to what the surgeon sees during a real surgical operation. The opacity of the tissues makes it difficult to plan an intervention without any risk for the patient (e.g. section of a vein or artery).

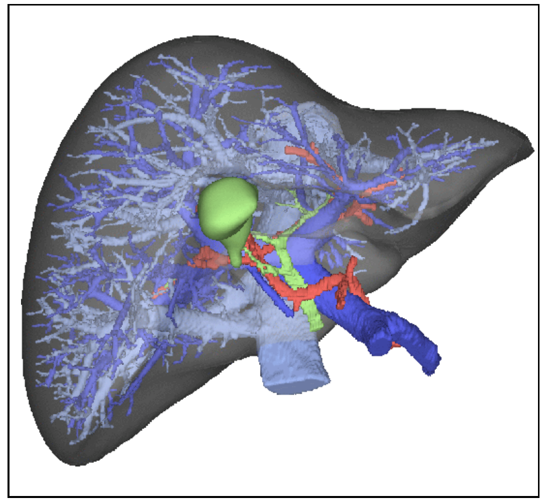

Figure 1-b
Transparent representation
With a transparent representation of the surface, the surgeon can estimate the relative positions of the tumor to be removed and the vascular trees. Thus, a planification of hepatectomy with minimal risks for the patient can be intended.

Figure 1: Anatomical models of the liver

2.2.1 Physical modeling

The organs of the human body are generally deformable and their law of deformation are often very complex. Many solutions have been proposed in the literature in order to model deformable objects, either in the field of computer graphics [11] [10] [6] or in a domain closer to biomechanics [12] [1]. We have opted for a simple model presenting attractive properties for fast computation of the deformations and reactive forces.

Elasticity theory has been often used [10] [8] [7] as a good approximation of the behaviour of a deformable body. The main interest of the elasticity problem lies in the stress-strain relation that gives the displacement of any point of an elastic body deformed under the action of a field of volumetric forces. But the resolution of the associated equations entails the use of a finite element method and makes it unsuitable for real time applications.

2.2.2 Force feedback

The force feedback system used in the simulator is a commercial product called *Laparoscopic Impulse Engine*. This device does not measure the forces exerted by the surgeon but only the displacements corresponding to the motion of the tool. Therefore, we have to solve a problem slightly different from the classical one, where our boundary conditions are mainly the displacements of the points of contact between the surgical tool and the body. According to these constraints, the solution of the equations of linear elasticity both gives the global deformation and reactive forces. Thus, the flow of information in the simulator forms a closed loop [4]: the model deforms according to the motion of the tool in the force feedback device, the force is computed in relation with the deformation and finally the loop is closed by generating this force through a mechanical transmission (fig. 2). However, for realistic sensations, the forces must be computed in the range of 500-1000Hz while 50Hz is enough for the visual feedback of the deformations.

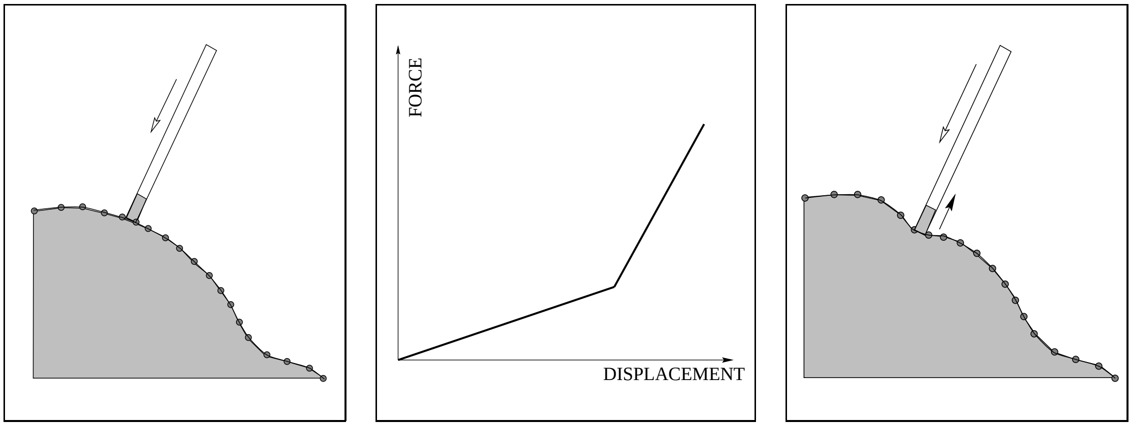

Figure 2-a
Deformation process
The motion of the tool induces some displacement constraints on the surface of the mesh.

Figure 2-b
Computation of the force
The reactive force is computed according to the previous displacement and the elasticity properties of the tissues.

Figure 2-c
Deformation process
About $\frac{1}{500}$ second later, the motion of the tool is constrained by the reactive force.

Figure 2: Force feedback loop

2.2.3 Speed up algorithm

In order to solve numerically the equations of linear elasticity, we have used a finite element method with tetrahedral elements. The use of this class of elements implies the decomposition of the volume into a set of tetrahedrons as mentioned in section 2.1. Through variational principles, the solution of the problem of elasticity theory becomes equivalent to the solution of a linear system:

$$[\boldsymbol{K}]\,[\boldsymbol{U}] \;=\; [\boldsymbol{F}] \tag{1}$$

where $[\boldsymbol{K}]$ is the stiffness matrix, $[\boldsymbol{U}]$ is the unknown displacement field and $[\boldsymbol{F}]$ the external forces. The size of this matrix $[\boldsymbol{K}]$ is $3\,n \times 3\,n$ where n is the number of vertices of the mesh. We immediately see that the size of the mesh (represented by the number of nodes of this mesh) is an important parameter influencing the computation time. The use of a good geometric representation and the possibility of simplifying it is consequently of prime importance. However, it is not sufficient to insure real-time interactivity.

In order to speed up the computations at an interactivity rate, we use the linearity and superposition principles. The latter property can be expressed as follows: the displacement of each point of the solid can be obtained by separately applying each force and then adding their various effects. Consequently, any deformation of an elastic organ can be obtained by linear combination of a set of "elementary" displacement fields. These fields are obtained by applying, at each node of the surface, an elementary displacement. The returned force at a given point of the surface is given by the same method. Thus, our algorithm allow us to compute, *in real time*, the deformations of a complex model *and* the force feedback component in spite of the high frequencies required in the simulation loop.

Figure 3-a
Laparoscopic surgery simulator
Our system for laparoscopic surgery simulation, including the working station and the force feedback device *Laparoscopic Impulse Engine*.

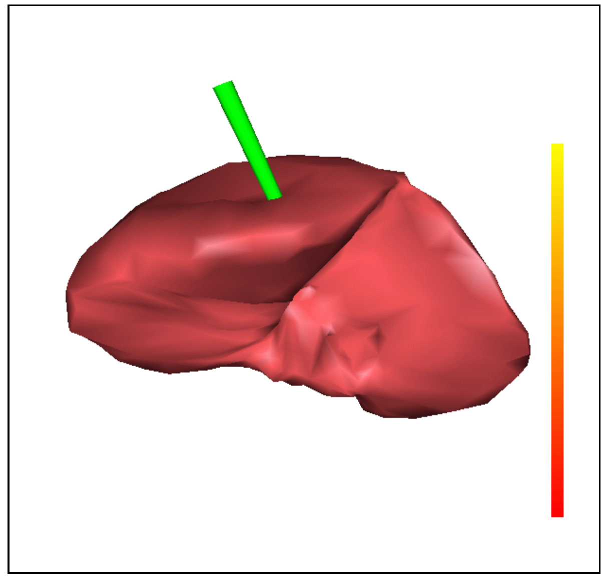

Figure 3-b
Deformation of an organ
As the virtual tool (cylindric stick) deforms the surface of the liver, a reactive force (vertical bar) is computed to simulate the resistance of the tissues.

Figure 3: Simulator of laparoscopic surgery

3 CONCLUSION AND PERSPECTIVES

The results presented in this paper show the first steps of the development of a laparoscopic surgery simulator. The originality of our method lies in the application of linear elasticity theory instead of the commonly used "mass-spring" methods. Thanks to our speed up algorithm, the computational time of the whole deformation is substantially lower than with these methods. Moreover, the elasticity properties of the tissues and the reactive forces are more easily derived from reality. We are now generalizing this method by building, with the same accuracy as the current model, patient-based models of the liver obtained from CT images. Thus, it will be possible for surgeons to train on virtual organs with a realistic geometry presenting pathological marks.

On the other hand, number of improvements have to be implemented for gesture training. Tissue cutting remains an important and unavoidable feature to ensure a realistic simulation. The introduction of neighbour organs is also necessary to help the surgeon for positioning his instruments. The contact between these organs and the target organ will also have to be determined.

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