Modeling the Dynamics of a Human Liver for a Minimally Invasive Surgery Simulator

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Abstract. Minimally invasive surgery techniques will probably be widely used in the near future for a large number of surgical procedures. However, these procedures are difficult to learn and high-fidelity computer simulation will be of great help to acquire these skills. In this paper, we describe how we have modeled a human liver for the purpose of developing an interactive dynamic simulator. This model makes use of a combination of 2D and 3D spring-dampers meshes to represent the heterogeneous mechanical characteristics of the liver. The related models and algorithms have been designed in order to obtain real-time responses to the operator actions, done using a virtual tool ...

1 Introduction

1.1 Motivations and Addressed Problems

Minimally invasive surgery techniques, i.e. surgery performed with instruments inserted through small incisions rather than by making a large incision to expose operation site, will probably be widely used in the near future for a large number of surgical procedures. The main advantage of this new technique is the reduced trauma to healthy tissue which is the leading cause of post-operative pain and long hospital stay of the patient. Consequently, minimally invasive surgery leads to significantly reduce the hospital stay and rest periods (and therefore the procedure's cost), at the expense of more difficult techniques performed by the surgeon. Such techniques require a long training period for the practitioner, involving appropriate computer graphics and Robotics tools. Thanks to the recent advances in computer graphics and processor technologies, it is now possible for researchers to begin exploring the issues involved in creating high-fidelity computer simulations of medical procedures. Such simulations require not only accurate geometric models of anatomical structures, but also realistic dynamic physical models for various tissues.

The purpose of this paper is to address this issue under a particular instance of the problem : how to model a human liver for obtaining a realistic real-time dynamic simulation of the liver behavior. The main characteristics of the problem that have to be considered for that purpose are that :

- The practitioner has to interact with the virtual liver using various interfaces (including a haptic interface). Consequently, the simulation process must satisfy real-time constraints. Moreover this simulation process must include appropriate procedures for detecting collisions and processing physical interactions;
- The simulated objects have complex geometric shapes, are volumetric and often non homogeneous. Both 2D and 3D models have to be used to obtain correct behaviors, and to make it possible to simulate the effects of physical interactions (collisions, cutting ...);
- The involved bodies seldom present a heterogeneous dynamic behavior, and tissues having various mechanical properties are in interaction (e.g. bones, muscles and blood).

In this paper, we propose a dynamic model of the liver which takes care into account the three previous characteristics. This model makes use of a combination of 2D and 3D spring-damper meshes to represent the heterogeneous mechanical characteristics of the liver. It allows to simulate in real-time the deformations of a liver subjected to interactions with a virtual tool. Such simulation includes body deformations, collision detection and physical interaction processing (e.g. sliding on the surface of the virtual liver using a virtual tool). This work has been performed within the framework of the French AISIM project aimed at developing techniques for computer assisted surgery.

1.2 Related Work

One of the main difficulty when developing a simulator for surgical operation, relies in the fact that the system allows interaction with a human operator in real-time, at least visually. The first simulators used 2D models (like in [3]), but such approach do not allow the simulation of complex physical interactions, like cutting operations, because all simulated bodies are hollow. The model proposed by Sagar et al.[12] allows a more realistic tissue simulation but it is exclusively dedicated to the simulation of interventions on the eye.

D. Terzopoulos and K. Waters [13] make use of a heterogeneous multi-layer spring-damper mesh to model a human face and to produce realistic facial animations. A bi-phasic elasticity is used to represent the nonlinear characteristics of the skin. But no geometrical collision detection and physical collision computation are implemented, which do not allow to interact with the model. Furthermore, because the model isn't volumetric, it's not relevant in our case.

M. Bro-Nielsen and S. Cotin [2] propose a volumetric model based on finite element method. This model makes it possible to simulate in haptic real-time volumetric objects composed of 500 nodes (inside and on the surface). But only an *homogeneous* elastic behavior is simulated. Moreover it is not possible to slide on the surface of the model with a virtual tool, but only to apply forces on the nodes of the external mesh.

2 Modeling the Liver

2.1 Main Physical Characteristics of a Human Liver

The liver is an organ located under the diaphragm, on the right, and weighs approximately 2.3 kg. Its mainly used to filter blood and to ensure a constant concentration of glucose.

From the mechanical point of view, the liver is a very malleable body (its exact shape strongly depends on the bodies which are in contact with it). It is composed of two major parts :

1. an internal friable material, the “Parenchyma”, which includes a complex vascular network (see fig.1);
2. an elastic skin called “Capsule of Glisson”.

Fig. 1. A human liver, along with its intern vascular network.

Intuitively, one could coarsely represent the liver by a sponge filled with an incompressible liquid and covered by an elastic skin. Since the liver is primarily composed of blood (an incompressible fluid) one can reasonably suppose that its volume remains constant[1].

2.2 Outline of the Model

The experimental knowledge acquired by peoples working in the framework of the French AISIM project (including a surgeon), along with the study of some surgical interventions videos, have shown that the Parenchyma is a volumetric deformable body made of a material so friable that it can be cut or destroyed without using a sharp tool : the simple fact of compressing appropriately the Parenchyma is sufficient to “break it up” (and thus cutting operations can be done in this way, see fig.2).

Other previous experimental studies has also shown that the Capsule of Glisson is mainly an elastic skin (i.e. a 2D elastic surface), which may easily be broken by the interaction with an external rigid tool [4].

Fig. 2. Laparoscopic operation : Parynchyma and Glisson Capsule.

Consequently a heterogeneous model is required for modeling the behavior of the liver. In the sequel, we show how we have modeled the liver using two main components : a 2D component for modeling the Capsule of Glisson and a 3D component for modeling the Parenchyma. Each of this models include a geometrical and a physical component.

2.3 Geometrical Component of the Model

The geometric component of the model is used for performing the display operations and for detecting the interactions. This model is also used as a spatial frame for constructing the physical component.

We have chosen to make use of 2D mesh of triangles (see fig.3), for representing the Capsule of Glisson, and a tetrahedric mesh for the Parenchyma (i.e. the interior of the liver). The triangular facets of the skin correspond to the external faces of the tetrahedra of the internal 3D mesh.

Fig. 3. A 2D mesh, representing the Capsule of Glisson of the liver (the associated 3D mesh representing the Parenchyma is not shown in the drawings).

2.4 Physical Component of the Model

The physical component of the model is used to compute the deformations of the liver resulting from the application of a set of external forces. These forces are either applied by the operator using the virtual tool (for instance controlled using a haptic interface), or generated by the physical interactions with other virtual objects of the scene.

The physical component is constructed from the 2D and 3D meshes (geometrical component of the model), by associating point masses to the nodes of the previous meshes and by adding spring-damper connectors between appropriate local subsets of point masses (see below). Two types of connectors are used for constructing this network : the “Linear Springs” and the “Torsion Springs” (see fig. 4).

The linear springs (denoted LS) are viscous-elastic components, whose main property is to give a viscous-elastic response to tensile forces. They are modelised by the following linear equation :

$$\mathbf{F}_a = (-\lambda\Delta d - \mu\dot{d})\mathbf{k}_a \quad (1)$$

where Δd is the relative variation of the distance between the two connected point masses, and $\dot{d}$ is the relative speed of the previous two point masses.

The torsion springs (denoted TS) are used to define angular viscous-elastic constraints between three connected point masses. Such connectors are used to maintain some curvature properties of the surface (represented by a 2D mesh) by giving a viscous-elastic response to torsion forces. They are modelised by the following equation :

$$\mathbf{F}_b = (-\lambda\Delta\theta - \mu\dot{\theta})\mathbf{k}_b \quad (2)$$

where $\Delta\theta$ is the relative variation of the angle described by the three connected point masses and $\dot{\theta}$ is the relative angular speed of the two point masses (see fig. 4).

Fig. 4. The two different kinds of connectors

In order to model the heterogeneousness of the liver, the connectors of the 2D mesh and of the 3D mesh are parameterized in such a way that they exhibit different mechanical characteristics :

- The Capsule of Glisson is modelised using almost quasi-elastic linear and torsion connectors (i.e. the viscous components are negligible). This approach allows us to obtain the elastic behavior previously mentioned (§ 2.1), and to bring back the Capsule of Glisson to its initial shape when no force is applied on it.
- The Parenchyma is modelised by a network of point masses and linear spring-damper connectors located respectively on the nodes and the edges of the 3D geometrical mesh. This network is constructed using quasi-viscous linear connectors (i.e. the elastic component is negligible). This approach allows us to obtain a plastic behavior (the internal material can easily be deformed, but it cannot go back alone to its initial shape).

Fig. 5. The hybrid mesh approach. A 2D and a 3D spring-damper meshes are used to model respectively the Capsule of Glisson and the Parenchyma.

The combination of the two previous models (the elastic skin and the viscous volumetric internal material) gives us the required global behavior for the virtual liver (the behavior of a “sponge full of liquid covered by an elastic skin”).

3 Outline of the Underlying Simulator System

The dynamic simulation of the liver has been achieved using the AlaDyn3D system developed by the SHARP research team.

This system allows the construction of complex physical scenes involving various interacting objects with different physical properties (deformable, rigid, friction, etc.) [9].

Object modeling The geometrical properties of an object are represented by a set of points and polygons which describe the surface of the object, and its interior. From this data the inertial matrix of rigid objects can be constructed through classical rigid body mechanics. For deformable objects the inertial properties of an object are implicitly defined by the distribution of the mass on its surface. These masses are interconnected by spring-damper connectors along the edges of the polygons, describing the constraint between pairs of masses.

Processing physical interactions Further, to detect the interaction between objects in a scene, a collision detection algorithm must be used. It is well known that collision detection is a computationally expensive task and a potential bottleneck in every application that aims to achieve real-time performance, such as in this case. For this reason it is essential to optimize the routines to their maximal extent. Gilbert et al.[7] have developed an algorithm which calculates, in linear time $O(n)$, the positive distance between the two convex bodies, and gives an approximation of the negative distance when ‘small’ inter-penetrations occur. Joukhadar et al.[10] extended this algorithm in order to obtain, in linear time, the points of contact on two deformable concave objects, as well as the direction of the contact and the volume of inter-penetration.

Once a collision has been detected an appropriate response must be computed. There exist several collision response models but for deformable objects the penalty method seems to be the most appropriate (N.B. impulse based methods make the assumption that a collision happens in a infinitely small interval of time, this clearly not being the case when dealing with deformable objects; see [5] for more details). Using this approach the force applied at a given point of an object where a collision has taken place is given by

$$\mathbf{F}_c = \begin{cases} (-\lambda v - \mu \dot{v}) \mathbf{k} & \text{if } v < 0 \\ \mathbf{0} & \text{otherwise} \end{cases} \quad (3)$$

where λ is the rigidity factor of the collision, μ is a damping factor (which represents the dissipation of energy), v the volume of inter-penetration, and $\mathbf{k}$ the contact direction.

Dynamic Equations Integration The integration method used in this simulator is the well-known explicit Newton-Euler. Using this method, point i of an object has the following update formulae.

$$\begin{aligned} v_i^{t+\Delta t} &= v_i^t + \Delta t a_i^t \\ x_i^{t+\Delta t} &= x_i^t + \Delta t v_i^t \end{aligned} \quad (4)$$

where Δt is the time step used and x_i , v_i and a_i are respectively the position, the speed and the acceleration of the point. This integration method, known for its small time step problem when dealing with rigid objects, is good enough for our application, because we are dealing with soft object.

Finally, an important stage is the parameters identification. Indeed the elasticity and viscosity of each spring of the mass-spring model must be defined, in order to match with the real behavior of the simulated objects. A genetic algorithm, described in [8], allows us to do this for each object, with respect to real data.

4 Implementation and Experimental Results

The machine used for these tests was a biPentiumII 300 (one of the two processors was in fact used for OpenGL software display). The AlaDyn3D system has been used and we have implemented in C++.

About the Real Time Constraint The implementation constraint imposed by the real-time requirement depend on the type of media which is used to communicate with the system. Indeed, the frequency which is needed for a visual output is really smaller that the one which is required to process a haptic output. For instance, S.J. Lederman et al.[11] recommend frequencies of about 300 Hz for a good perception of the forces and about 1000 Hz to feel the textures.

For graphic interfaces a rate of 25 images is usually used.

Quantitative Results We have used as input a 2D mesh of the liver imported from the project “Visible Man”. This 2D mesh has been pre-processed in order to reduce the number of facets, to smooth it, and to obtain the internal tetrahedric mesh (which has been calculated using the GHS3D[6] software of INRIA).

Then we have used this 2D and 3D meshes to generate the spring-dampers network (see § 2.4). For the purpose of the dynamic simulation, the model of the liver has been placed in an empty space, without gravity, but with a slight environmental viscosity. A virtual tool, simulated by a rigid object controlled in position by the operator, makes it possible to apply forces to the model of the liver, and to follow compliantly the external boundaries of the virtual liver.

Table 1 shows the numbers of states of the system calculated per second of simulation according to the mesh used.

facets	tetrahedrons	states calculated per second
1224	6291	0.3
500	1974	12
320	1576	20

Table 1. Experimental results obtained for three layers of representation of the liver

We thus obtain a “comfortable” visual real-time performance for the coarsest grid and a “satisfactory” real-time performance for the intermediate mesh. For the finest mesh, the simulator was not fast enough to provide real-time simulations.

In the experiments, the simulations of the liver responses to various actions of the operator has shown qualitatively realistic behaviors : the liver was locally deformed under the effects of the forces applied using the rigid virtual tool and it went back to its initial shape as soon as no forces is applied to it. It was also possible to smoothly slide along its external surface, using the virtual tool.

Furthermore, if the operator, after having strongly pressed the liver, withdraws the tool, the liver didn't return fully to its initial shape (since it was submitted to a plastic deformation, see fig.6). This is due to the strong viscosity of the connectors of the Parenchyma, and simulates the malleable characteristic of the liver. Nevertheless, a real liver should finally come back slowly to its initial shape, that is not modelised in our case.

Although the constant volume constraint is not implemented in our simulator, we have observed that the volume of our liver model doesn't change more than 5%, according the operator applies small forces.

This model presents *qualitatively* a mechanical behavior which is closed to that of a real liver. It remains to find the exact numerical values of the parameters of elasticity and viscosity of the Parenchyma and the Capsule of Glisson. However, no force/displacement physical data is available yet, because of the difficulty in making the measurements *in vivo* (the liver being made up mainly of blood, its dynamic behavior is very different when not irrigated, because blood coagulates quickly). Such data should be available within the scope of the AISIM project, in a few months.

Fig. 6. An example of simulation. On the left is the initial configuration, on the middle and right is the system during manipulation

5 Conclusion and Perspectives

We have presented a heterogeneous volumetric model of the liver based on a mass-spring model. In conformity with the reality, our model presents two different dynamic behaviors for the Parenchyma and the Capsule of Glisson. The optimized collisions detection algorithm of AlaDyn3D makes possible to interact on the model in visual real-time using a virtual tool controlled in position.

But it's important to remember that the elasticity and viscosity parameters of our model were chosen intuitively, to obtain a good *qualitative* behavior at a good simulation frequency, so we strongly need real strain/displacement data to adjust our model.

The current work focuses on the three following points:

- The implementation of an algorithm allowing us to *interactively* modify the topology of the liver, and thus to carry out cutting operations;

- The identification and modification of the parameters of some connectors of the internal 3D mesh, in order to obtain a viscous-elastic behavior for modelling the internal vascular network of the liver (see fig.1);
- The optimization of the model in order to obtain a haptic real-time interface, thanks to the use of a dynamic refinement algorithm of the spring-damper mesh or an other numeric scheme for the integration of dynamic equations.

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