VR Simulation of Abdominal Trauma Surgery

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Abstract.

In this paper we describe a simulation test-bed we have developed for training of abdominal trauma surgery.

The abdominal surgery scene is highly complex and contains many layers of deformable organs. Representing this layered and deformable anatomy with models that can interact, be probed and cut presents a unique challenge. We have met this challenge by applying a variety of technology advances in deformable models, computer graphics, and force-feedback (haptic) interfaces.

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1. Introduction

Simulation of open surgery has always been one of the most challenging problems for anyone developing surgery simulation system. Unfortunately, it has remained an elusive goal, largely considered impossible with the current technology.

The biggest challenge, of course, is the fact that surgeons use their hands extensively during surgery to directly manipulate organs and tissue. The human hand is an incredibly sensitive and versatile instrument. To develop a virtual environment which would react realistically to the actions of a hand, and at the same time provide the required degree of haptic stimulation, is simply impossible using today's technology.

But just how far have we actually traveled towards that elusive goal? We will try to answer these questions in this paper by describing the HT Abdominal Trauma Simulator (HATS) test-bed. This simulator has been developed for open surgery from the front to remove a kidney that has been shattered as the result of a blunt trauma to the body.

At some time during the project it became clear that it would never be possible to model realistically the complex interaction between a surgeon's hands and the contents of the abdominal cavity. The only way it would be possible to train these steps of the procedure was by substituting them with something else which could provide at least some level of cognitive training.

In the end, the simulator has become a test-bed for the implementation of a range of different simulation techniques with varying levels of realism and immersion. Some of these can be characterized as multimedia style, while others are full-blown haptics and physics simulations.

1.1 Related work

Most of the early work on surgical simulators for surgery in the abdomen and other soft objects has been characterized by the application of one particular physical model.

Cover et al. [5] were the first to present real-time models for surgery simulation. They used a simple surface-based mass-spring model to simulate deformation of a gallbladder. Kuhn, Kuhnapfel et al. [8] have implemented mass-spring models in the KISMET simulation system. Although their models in principle are surface models, they introduce volumetric behavior by including parent nodes that connect nodes on different sides of an object. Surface models are also used in the commercial Teleos software [9] developed by HT Medical, Inc. Teleos uses tubular spline surface models and can model simple structures derived from the tubular topology (e.g. arteries, gall-bladder).

Implicitly solved finite element systems have been used in the on-going parallel work of Bro-Nielsen [1,3] and Cotin et al. [4]. These models present a better and faster solution to the deformation problem than mass-spring models. But at the same time they are more complex. See [3] for a discussion of finite element models and their comparison to mass-spring models.

In later years, the technology for deforming organs in has become quite well understood. There are still a lot to learn, but the available models can solve a range of problems. As a consequence, several realistic simulators have started to appear. Most authors are taking a more systems-like approach to surgical simulation.

Sagar et al. [10] have presented an eye surgery simulator using non-linear finite element models to model deformation of an eye. This system is complete with force-feedback and allows cutting in the eye. The work of Kuhn, Kuhnapfel et al. [8], which we mentioned above, also represents an interesting system for laparascopic gall-bladder surgery.

In [7], Gibson et al. presented some early results of their effort to develop an arthroscopic knee surgery simulator. This simulator uses a new volumetric approach to model organs. Although this is a promising technique for the future, computers are probably still too slow to allow realistic deformation of a volumetric representation. Recently, Wiet et al. have presented an endoscopic sinus surgery simulator [11] which is based on the use of volumetric models too. A characteristic of both of these simulators is that they operate in a scene that is mostly rigid. The amount of deformation is limited and can therefore be handled with simple and fast algorithms.

At HT Medical we have developed a number of simulator systems in recent years, including simulators for neuro-endoscopic surgery, interventional radiology, rigid bronchoscopy, and flexible ureteroscopy. [2] contains a description of these simulators.

2. Purpose

To describe the medical procedure we developed a set of storyboards that showed the approach in detailed steps. These storyboards were very useful both in terms of guiding the development of the technical systems for the simulator and also as the basis for multi-media guidance during the simulation.

Some of the steps in the procedure are difficult or impossible to model realistically. Instead we had to substitute some of the training steps with different degrees of non-immersive simulation. At the very least we tried to illustrate a step to provide some level of cognitive training to the trainee.

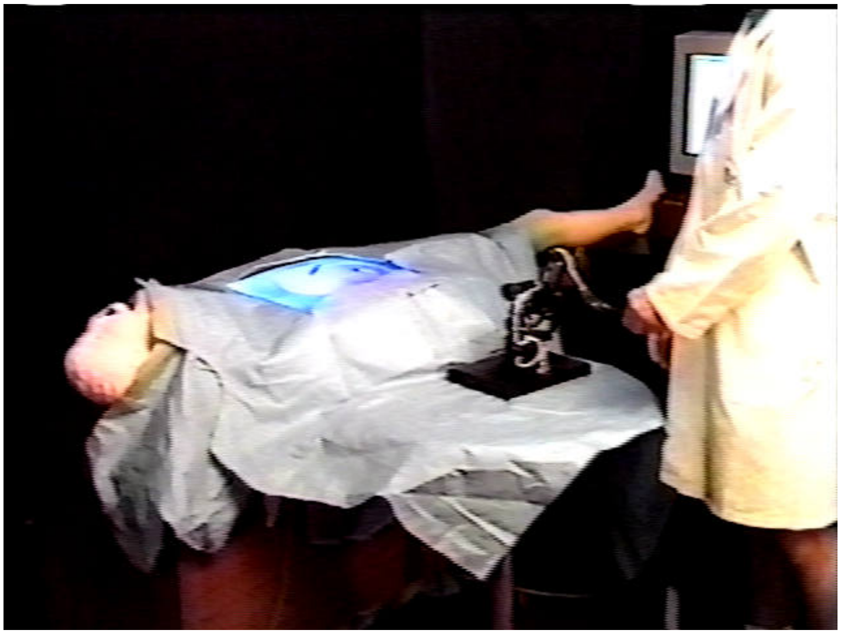


Figure 1. General setup of the simulation system.

3. Methods

The simulation test-bed has been configured to look like a real patient lying on a surgery table. The patient's abdomen is exposed and the rest of the patient's body is covered by blue surgical draping. To accomplish this, the computer monitor is mounted horizontally into a special purpose stand that has the head and legs of a mannequin attached to it. The computer monitor serves as the exposed abdomen and it is camouflaged using the blue surgical draping. An overview of the simulation setup is shown in figure 1.

3.1 Software architecture

The software for the simulator has been built as a multi-media system with VR simulation, Patient records (GUI), and Training instructions and guidance (GUI) (see figure 2).

The latter two components are contained in a Graphical User Interface (GUI) that has the appearance of the standard manila folder used by many American medical institutions to store patient information. The GUI is shown in figure 3.

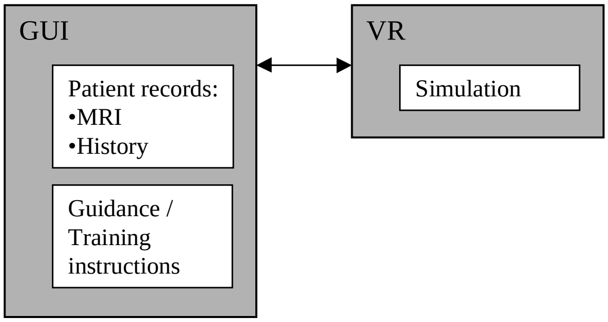
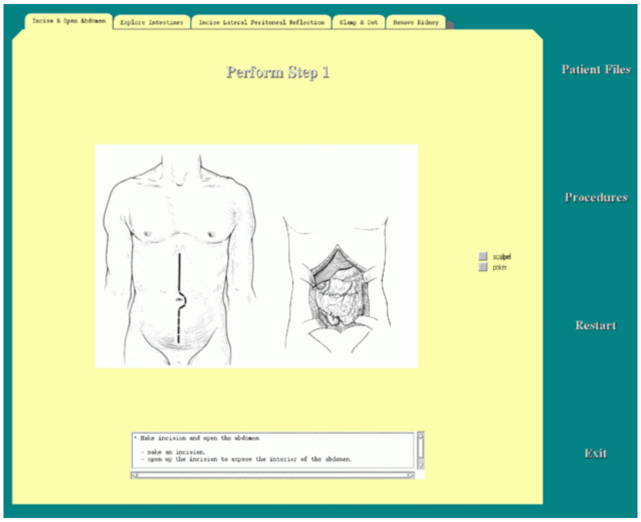


Figure 2. Multimedia framework



* Make incision and open the abdomen

  - make an incision.
  - open up the incision to expose the interior of the abdomen.

Figure 3. Graphical User Interface.

Because of the computational load of this sort of simulation system, the software has been developed as a real-time distributed software system designed to run on different computers linked with an ethernet. The software contains at least 6 independent software processes that take care of different components of the simulation.

We analyzed the communication between the different processes and found that the best way to divide the processes was by putting haptics and collision detection on one computer, and the remaining processes on another computer - both having shared memory between their respective processes.

In practice a 4 processor SGI ONYX-2 shared memory parallel processing computer served as the main platform and a SGI IMPACT as an additional compute server. To implement the communication between the two computers we used the Parallel Virtual Machine (PVM) [6] communication protocol. The system diagram is shown in figure 4.

3.2 Physical models

For the deformation of surfaces, we have used standard mass-spring systems (simplified FEM models, see [3]). A mass-spring system consists of a number of vertices with masses, and a set of springs connecting these vertices. In addition, we have added strut springs that anchor the mass-spring surface to a particular default shape and position. When the resulting explicit mathematical problem is solved in real-time, the surface deforms with a physically-based behavior in response to external stimuli. An example of a deforming stomach is shown in figure 5.

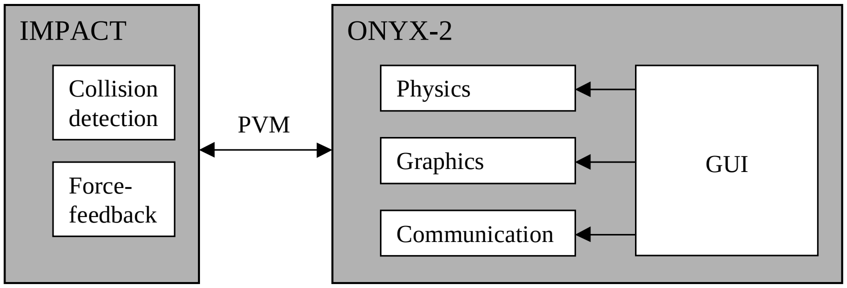


Figure 4. Processes on the two computers.

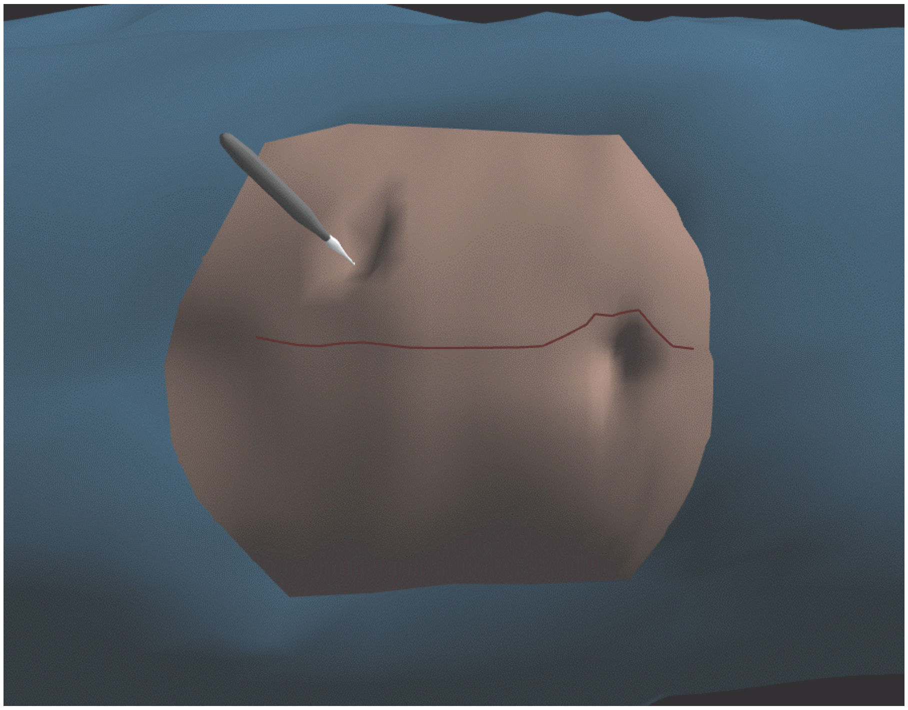


Figure 5. Instrument deforming stomach.

The reason why a more complex FEM system was not used for these surface models, is that they had to be cut to accommodate incisions. This is only reasonable with mathematically explicit models such as mass-spring models (see [3] for a discussion).

Cutting is accomplished using a complex set of basic operations applied to individual triangles. Taking into account the range of different cases corresponding to cutting from an edge to another edge, a corner to an edge, the interior of a triangle to an edge, etc. yields a dozen different cases. In each of these cases all the dependencies in the general model have to be updated which is not a trivial task.

For arteries and other tubular models we are using a simple linear mass-spring model as the spine of a tubular structure based on connected contours. Each of the contours are linked to a mass-vertex on the spine, and thus controlled by it.

We are considering at the moment to use Fast Finite Elements [1,3] to model deformation of the shattered kidney after it has been extracted. But for practical reasons we have not implemented this yet.

Finally, we have implemented a bleeding algorithm that uses a diffusion-style algorithm to model the flow of blood on the surface of polygonal models. For performance and complexity reasons the blood is stored only at the vertices of the polygonal surface. This limits the precision of the blood movement to the distance between polygon vertices, but allows the cutting algorithm to be used on the bleeding surface as well.

In addition to modeling the flow of the blood, the algorithm also modifies the polygonal surface using a bump-mapping approach to provide the illusion of blood lying on top of the polygonal model. At rendering time a vertex with blood on it is moved in the normal direction of the surface. The distance is determined based on the amount of blood on the vertex.

3.3 Collision detection and haptics

We have been using the SenSable Technologies Phantom haptic interface device to gather 3D positioning input and provide force-feedback. This device provides 6 degrees of freedom for position and 3 degrees of free for force-feedback.

Instead of developing the basic force-feedback software, we have used the SenSable Technologies GHOST software package. GHOST implements basic collision detection and force-feedback and we have used it as the basic component in the system for collision detection and force-feedback. Around it we had added intelligent control of models, model complexity, and force-feedback characteristics for deformable models.

4. Results

A typical screenshot from the simulation system is shown in figure 6. The user interacts with the system using a mouse for the GUI interface and the Phantom haptic interface device for the VR simulation.

5. Conclusion

We have developed a surgical simulation test-bed for training the removal of a shattered kidney by open surgery from the front of a trauma patient. This kind of surgery is particularly complex and difficult to simulate, and the simulator cannot be characterized as being fully realistic. With current computers and technology it is not possible to develop completely life-like simulators for open surgery.

But developing the test-bed has allowed us to study the interaction of a number of different technologies for deformable models, cutting, bleeding, haptic modeling, interprocess communication, and multi-media interfaces.

The simulator includes some of the newest advances in deformable models and related technologies and we expect that we will be able to incorporate some of these technologies in future simulators developed at HT Medical, Inc.

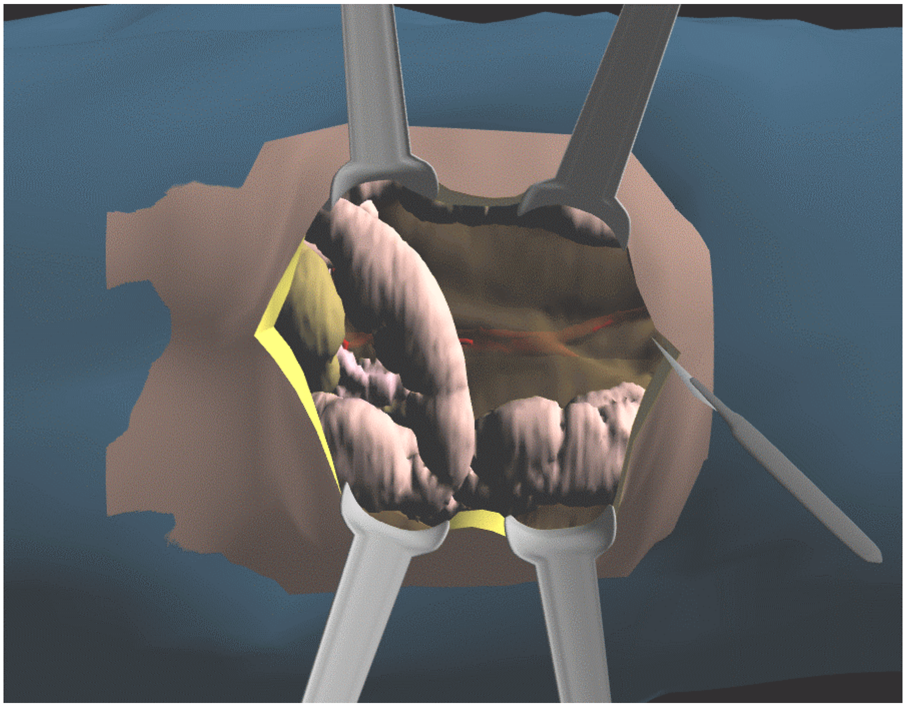


Figure 6. Stomach after initial incision has been performed.

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