Simulation techniques for minimally invasive surgery

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1. SUMMARY

Surgery simulation technology has made strong progress in recent years. This has come both from development of new basic technology, and from actual implementation of this technology in practical surgery simulation systems. This paper provides an overview of the basic issues in surgery simulation development. Issues such as procedural versus skills simulators, and the relationship between the type of surgery and the necessary level of technology are addressed in turn. In addition, we demonstrate some of the results achieved at HT Medical, Inc. to show the applicability of the techniques described in the paper.

Keywords: Surgery simulation, haptic interface, physical models

2. INTRODUCTION

The success of flight simulators provides a convincing example of the importance of simulation technology when applied to the teaching of abilities which have an impact on human lives. It also provides important examples of both the value of early simplistic simulators and the long-term potential of simulation techniques when applied to a field. Just as early flight simulators were met with considerable skepticism, early surgery simulators have often been criticized for being too simplistic and not realistic.

But this is changing. The technology for simulation of surgical procedures has improved dramatically in recent years. By using new advances in computer graphics and physical modeling techniques, and at the same time concentrating on specific medical procedures, very realistic simulation systems have been created. Especially in the field of minimally invasive procedures, a range of different simulation systems have been presented by both academic institutions and commercial companies. These simulation systems have demonstrated the feasibility of the technology, and commercial systems are currently under development.

An important aspect of recent practical simulation systems is the emphasis on teaching procedures rather than motor skills. Although motor skills are very important, they depend very much on the physical sensation of touching anatomic structures. Although touch can be modeled today, it is difficult to provide the very accurate feeling needed for learning these skills properly.

By concentrating instead on teaching medical procedures rather than motor skills, and thereby diverting the attention to more content specific issues, these recent simulators have avoided the risk of disappointing the user.

Collaboration with medical professionals is very important for development of procedural surgery simulators, and the most successful companies and research laboratories have a strong relationship with practicing clinicians. It has, therefore, been very positive to see the growing interest in the medical community for getting involved in the early stages of this coming revolution of medical training.

The purpose of this paper is to present some of the technology issues which confront surgery simulation developers today. We will do this by discussing some of the basic technology that categorizes surgery simulation systems, and showing some of the procedural simulation systems that have been produced by HT Medical, Inc.

3. METHODS

The character of a minimally invasive surgery simulation system is determined mainly by the type of instruments used for interaction with the patient and the influence these instruments have on the patient.

Minimally invasive instruments come in increasingly different shapes and materials based on the requirements of the medical procedure and the anatomy involved in it. Some instruments are just rigid scopes such as those used in bronchoscopy examinations, whereas others are flexible, and multi-layered such as catheters for coronary angioplasty.

Both the actual medical procedure and the choice of instruments have an important impact on the necessary kind of tissue simulation. While a very flexible coronary catheter does not change the shape of an artery significantly, a rigid bronchoscope can dramatically deform the inside of the trachea. Apart from changing the shape of the anatomy, the procedure may call for resection or removal of tissue and organs, such as removal of the gall-bladder using laparascopic procedures.

To the surgery simulation system developer, shape changes and modifications to the anatomy are very different. To understand this, the reader should bear in mind that a simulation system typically consists of a number of models of anatomical organs with associated physical behaviors and computer graphics representations. These models require considerable pre-computation time and can be very complex.

~~Since~~ Changes in shape are usually the result of applied forces by a surgical instrument, and can be determined using the pre-computed physical behavior model stored in the organ models. The physical behavior model contains information about the elasticity, weight, etc. of the organ, and computing shape changes using this information is relatively simple.

On the other hand, when the surgeon takes a tissue sample, makes an incision in the liver, or separates the gall-bladder from the liver, it involves modifications of the patient anatomy and therefore generally modifications to the computer models of the patient organs. Depending on the amount of information which has been pre-computed and the character of the modification, the computation time for restoring or modifying the computer models can be quite large.

Naturally, during development of a surgery simulation system the developers work closely with medical professionals to determine the modifications that are necessary for a particular medical procedure. Often cases only a few types of incisions or resections are necessary. In these cases it is possible to pre-compute the changes to the computer models in response to the anatomy modification and store them in the
computer memory.

Based on the need for shape changes in the medical simulation, the scope of simulation techniques for anatomic models is very broad. They range over:

- Static computer graphics models. E.g. used in endoscopic examinations [Lorensen et al., 1995] and for the arteries in coronary angioplasty [Higgins et al., 1995],
- Animated physically-based deformations. E.g. used currently at HT Medical for development of the bronchoscopy simulator - see below,
- Deformable mass-spring models. E.g. used in laparascopic gall-bladder removal [Kuhn et al., 1996] and the HT Medical Teleos simulation framework [Merril et al., 1994],
- Advanced fast finite element models. E.g. demonstrated for liver-surgery and general tissue deformation [Bro-Nielsen et al., 1996; Cotin et al., 1996] and currently used by HT Medical in the development of the DARPA Trauma Simulator.

These techniques are very different both in terms of mathematical theory, and with respect to the computational complexity.

But, due to the very complex visco-elastic behavior of human tissue, none of these mathematical models can be characterized as being accurate. Consequently, it does not make sense to perform very precise physical measurements of human tissue parameters, since current mathematical models cannot use or benefit from these parameters. Instead parameters are typically determined by comparing video tapes of real surgery with the simulation results, and making adjustments to obtain visually close results. In some cases this is combined with simple tissue experiments to obtain rough initial estimates of the model parameters. Naturally, as computers become more powerful, more advanced and accurate mathematical models will be used. At that point, precise measurements of tissue parameters becomes an important issue.

In addition to anatomy,

Often instruments have to be modeled using physical models too. Good examples are the flexible catheter in coronary angioplasty, and a flexible bronchoscope. Naturally, the same considerations that were used for the anatomy models above must be applied to the instrument models. When a surgery simulation project is started it is, consequently, very important to determine accurately the necessary level of simulation technology. This choice has strong implications on the costs and feasibility of the project.

To allow the surgeon or radiologist to feel the interaction with the patient anatomy, the computer has to do more than just track the surgeon's instruments and model the shape changes and model modifications. It must also provide artificial forces to mimic the reaction of an organ when the instrument touches it. This kind of computer interface is called a haptic interface, which literally means an interface that gives the user a sense of touch.

A couple of haptic interfaces are available commercially. This includes the PHANToM device from SensABLE Devices, and the Impulse Engine from Immersion Corporation. But, only a limited range of instruments can be simulated using these general devices. HT Medical has, therefore, in many cases worked closely with the device manufacturers to develop custom haptic devices for procedures such as neuro-endoscopy and interventional radiology. Developing these devices is a significant obstacle for many simulation projects, and additional research is currently being directed towards solving the associated challenges.

4. RESULTS

As a result of HT Medical's commitment to surgical simulation and research into the basic technologies of this field, HT Medical has produced some of the most advanced surgical simulation systems. This section gives a broad overview of some of these applications of the technology described above.

4.1 Neuro-endoscopic simulator

HT Medical designed the virtual neuro-endoscopy simulator, for exploration of the ventricular system of the central nervous system (see figure 1 and 2). A cast of the third and lateral ventricles was digitized to provide the geometric model, and medical illustrations provided the texture maps for lining of the ventricles, including blood vessels and the choroid plexus. The user is able to navigate throughout the ventricles using an endoscopic device threaded through the top of a mannequin. The actual endoscope is flexible and the simulator, therefore, allows for bending of the endoscope whenever it touches the interior walls of the ventricles.

4.2 Interventional radiology simulator

The ’Dawson-Kaufman’ Interventional Radiology simulator, allows physicians to practice angioplasty and other techniques for opening blocked arteries in a setting that duplicates the look and feel of a real procedure (see figure 3). The simulation is based on real patient cases and uses a video monitor that duplicates the black-and-white x-ray pictures that interventional radiologists actually watch on a fluoroscopic screen. The simulator also incorporates tactile feedback so that physicians manipulating guide wires and catheters "feel" sensations actually experienced during the procedure, such as encountering an obstruction in an artery.

4.3 Rigid bronchoscopy simulator

Based on preliminary quantitative evaluation, Penn State’s Hershey Medical Center (HMC) concluded that virtual reality training at their teaching hospital could tremendously reduce their OR-based training time and costs. HMC partnered with HT Medical to create a bronchoscopy simulator - the first of several training simulators for their ‘Virtual Operating Room’ (see figure 4). The simulator includes pediatric and adult cases, and utilizes a rigid scope to explore the bronchi and diagnose subtle abnormalities. The next phase of this bronchoscopy simulator will include therapeutic procedures, including removal of foreign bodies.

4.4 Flexible uretetoscope simulator

The HT Medical ureteroscopy simulator allows physicians to explore and diagnose the kidneys for the possible existence of tumors, stones, and air bubbles by simulating a minimally invasive endoscopic technique where a small-caliber, flexible-fiber optic endoscope is passed through the urinary tract. The simulator also contains timers built into the software to allow assessment of the amount of time that the user requires to navigate up the ureter and through the inside of the kidney. HT Medical commissioned Immersion Corporation to design and implement a custom input device by using an actual flexible ureteroscope supplied by Karl Storz Endoscopy America.

4.5 DARPA shattered kidney trauma simulator

From the U.S. Defense Advanced Research Projects Agency (DARPA), HT Medical has received a grant to develop virtual reality software that depicts damage to the abdomen, including the spleen and the kidneys. This software will be used in conjunction with DARPA's Battlefield of the Future program.

5. Discussions

Surgery simulation technology has come a long way towards making specialized surgery simulation systems for minimally invasive surgery possible. There are still a range of issues that have to be solved. In particular, creating haptic interfaces that provide the exact look and feel of the original instruments is quite difficult. But, by adding more medical content and focusing on the procedural aspects of the training rather than skills training, HT has been able to create simulation systems that show the validity of our general approach.

HT is now in the process of developing a new generation of procedural simulators for wide-spread use in health-care institutions. One of the key goals is to ensure that these systems will be both affordable and cost-effective. We hope to achieve these goals by using the experience and technology gained from previously developed simulators. At the same time computer hardware technology is lending a helping hand as the computers continue to drop in price.

7. References

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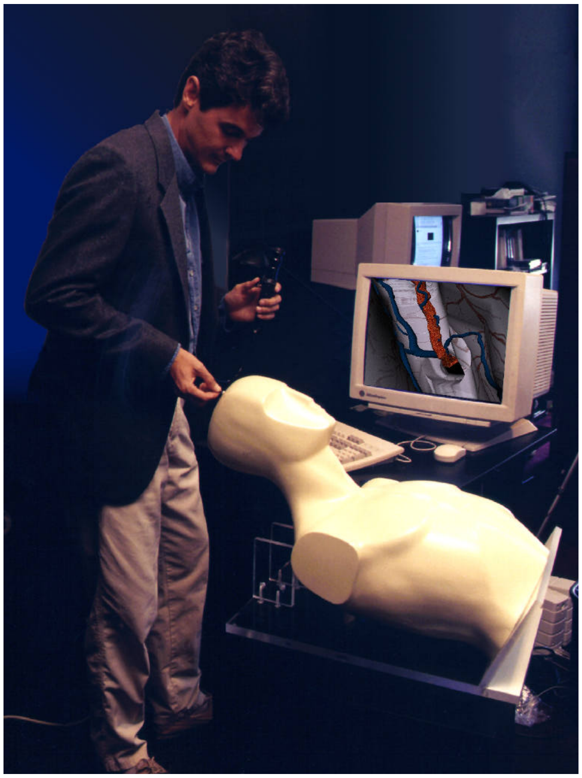

Figure 1. The HT Medical neuro-endoscopic surgery simulator. The haptic interface is inserted into the head of the mannequin doll, and the simulated view of the scope is shown on the computer screen.

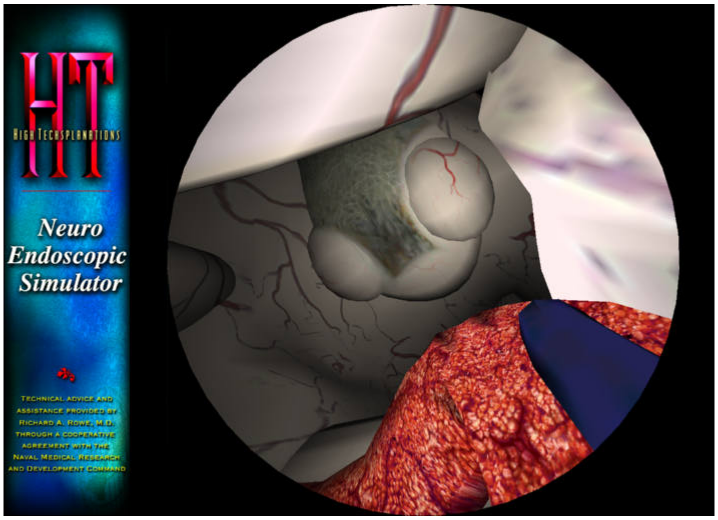

Figure 2. View of the ventricular horns in the HT Medical neuro-endoscopic simulator.

Figure 3. The HT Medical interventional radiology simulator. The haptic interface is shown with an example of the computer generated X-ray display.

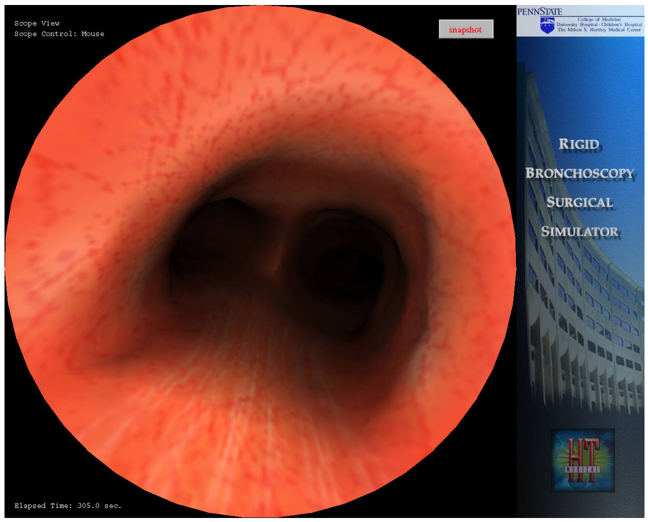

Figure 4. View down through the trachea in the HT Medical bronchoscopy simulator.