

MAKING SURGICAL SIMULATIONS A REALITY: TECHNICAL AND PRACTICAL ISSUES FOR APPLICATIONS IN MEDICINE

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Summary

Surgical simulators have been developed especially in the past few years for enhancing the training of physicians, reducing the number of animals and cadavers, flexibility of training scenarios and for preoperative planning. Despite their potential benefits, and the fact that they have precedence in flight simulators, there are very few simulators in current use. This is primarily due to the lack of understanding of fundamentally what is required for them to be useful, and the fact that the problem is interdisciplinary. This interdisciplinary nature has led to difficulties in forming a productive team. In this paper, we discuss the technical and practical issues in developing useful surgical simulators. Two case studies representative of the strengths of weaknesses of the technology is presented, including simulation of procedures in the Cryotherapy of the prostate and interventional radiology.

Introduction

Surgical simulators have been developed especially in the past few years for enhancing the training of physicians, reducing the number of animals and cadavers, flexibility of training scenarios and for preoperative planning. Such simulators can be used to allow the physician-in-training to master both conventional treatment protocols and also rarely encountered problem situations prior to his or her first encounter with an actual patient in a hospital setting. It also has the potential to allow experienced physicians to hone their skills or to try out new therapies in a risk-free environment. Besides the obvious benefits in terms of patient safety, savings in operating room hourly costs could make this kind of simulator an extremely cost-effective tool with which to educate physicians.

Despite their potential benefits, and the fact that they have precedence in flight simulators, there are very few simulators in current use. This is primarily due to the lack of understanding of fundamentally what is required for them to be useful, and the fact that the problem is interdisciplinary.

Fundamental in having a successful simulator is to understand the different kinds of simulators that are useful. There are no single goals of simulators. Full simulators try to replicate every facet of a procedure. This is equivalent “full motion simulators” in the aviation training simulators. One of the pitfalls of current development is that many consider this to be the only simulators that are useful. Since the technology is still lacking, especially in reproducing the haptics of the simulation, such approaches tend to be difficult to realize. Part-task trainers try to replicate some part or aspect of the procedure. This is equivalent to “IFR approach” simulators in

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the aviation industry. Feedback not necessary to train the particular task need not be replicated. For example, haptics, often thought of as essential for successful simulators, is not necessary if the task is to see the relationship of a temperature display to an ultrasound image. Finally procedural trainers take students through the algorithm of the particular procedure. This may be implemented through a CD-ROM multimedia presentation along with some basic interaction (in choosing a particular action from a list). Each type of simulators is useful in their own right, as can be seen in their use in the aviation training.

A second feature of a medical simulator is the fact that fundamentally, it is an interdisciplinary problem. The problem requires the co-operative efforts of computer scientists (simulation, visualization, interfaces), medical professionals (physiology, anatomy, domain knowledge), and cognitive scientists (learning theory, retention, transfer, performance). Everyone speaks a different language and traditionally, there is very little overlap among the disciplines. One of the most difficult aspects of the problem has been in getting everyone to learn and respect aspects of each other's disciplines. There also tends to be clinical resistance in the use of simulators. Physicians have been trained traditionally without the use of computer-based trainers and the general attitude tends to be that simulators are not necessary since there are not enough clinical cases.

An aspect that is often overlooked has to do with training issues. This is necessary for deciding if the trainer should be part or whole trainers. The decision on the kind of guidance that will be provided needs to be made. Many cues that may not be available in real procedures may be useful in some cases. The kind of feedback will be provided include performance in terms of time and outcomes as well as those required to perform the procedure. A determination of the performance metric is necessary, including perceptual-motor as well as knowledge metrics. Finally, it is important to validate the simulator. The issues of importance are transfer which tries to answer the question: "Does training on the simulator improve real performance?" What is the correlation between the simulator and real performance? Can an expert perform better on the simulator than a novice? Is the scope of the simulator valid?

The technical issues involve four major components: tissue modeling, building virtual patients, rendering, and interfaces. Tissue modeling can be either physics-based or kinematic. Due to the real-time limitation of a simulator, hybrid approaches are often used that take the essential features of the physics and encapsulate them into a kinematic model. Collision detection is a major issue due to the inherent complexity of the problem. Real tissues tend to be complex (non-linear, viscoelastic, non-homogeneous and anisotropic). A model can be derived through biomechanics, in/ex vivo testing, and force sensors on real instruments. Building virtual patients involve generating the geometric shape often through segmentation of volumetric data. The use of multi-modal data requires registration. The resultant model can be either surface or volume representation. Surface representations are easier to render but difficult to model manipulation of tissue, such as cutting and suturing. If the data is from a particular patient, it can be used for pre-surgery rehearsal, whereas generic data is applicable for use in training systems. Rendering is primarily driven by the real-time performance requirements. This usually means the use of hardware rendering and texture mapping. Interfaces are dependent on whether tactile feedback is necessary. General purpose devices, such as the Phantom can be used for some applications. However, for most applications, a special purpose device may be necessary.

In the following sections, we will describe two case studies in surgical simulators: one on interventional radiology and another one on the cryotherapy of the prostate. The work was performed at the Laboratory for Advanced Computer Applications in Medicine (LACAM). LACAM is an interdisciplinary team effort involving faculty and students from a number of

departments within two schools; the School of Engineering and Applied Science and the School of Medicine and Health Sciences at the George Washington University. LACAM has been involved in development of a surgical simulator for a number of procedures.

Interventional Radiology

One of the reasons that surgical simulators has gained attention for training physicians is the prevalence of minimally invasive procedures. Such procedures as endoscopy, laparoscopy, and catheterization force the physician to interact with the patient through an instrument, allowing him/her only limited bandwidth of senses. This makes the procedures difficult to master without extensive practice. To date many procedures have to be practiced on animals, a method which is very expensive and can be questioned on an animal rights ethics basis. However, it is relatively easy to reproduce such procedures in surgical simulators with limited interaction modes.

Inferior vena cava (IVC) filter placement is a procedure used to insert a filter in the IVC using a catheter. The filter is used to prevent blood clots, which could dislodge from the veins of the lower extremities and pelvis, from traveling through the IVC into the heart and then into the lungs causing a pulmonary embolus. If the blood clot is large enough and obstructs blood flow to the alveoli in the lung, the patient will not get enough oxygen into the blood and could die.

In the system, patient data acquired from MRI scans is processed to create two databases. A segmentation process extracts a blood vessel structure. An x-ray casting process prepares a representation of the overall anatomy. The system also maintains a current model of the inserted catheter. The simulation updates this model as the user inserts and twists the catheter through the haptic interface. Appropriate force feedback is generated by the simulation and felt by the user through the device. The anatomic, vessel and catheter data are combined in the rendering process to create the fluoroscopic display. The user also interacts with the testing and tutorial system.

A data structure representing the vasculature of the patient is developed from the input scan data. This data structure is used for three major purposes: visualizing the fluoroscopic image, geometric operations such as detecting collision between the catheter and the vessel wall, and dynamic simulation of the forces felt by the user. It is difficult to develop one geometric model that efficiently serves all three sets of requirements. Instead, we extract an abstract structure from which appropriate structures can be generated to efficiently allow the operations.

The abstract model of the venous system is a tree structure in which the nodes store important features of the vessel, such as the location of the centroid, diameter, and tangent vectors at important points, such as bifurcations or areas of rapid parameter change. Ideally, this compact representation should contain enough information to exactly recreate the original vessel structure. Such a structure cannot be designed using techniques such as marching cubes [5] which allow the extraction of raw geometry, but do not allow the geometric relationships between different parts to be represented. Instead, we use a technique that uses ray-shooting to determine curvature and recursive subdivision to identify essential features.

The interventional radiologic procedure we are simulating requires the physician to use x-ray images of the patient to aid in navigating the catheter through the venous system. During an operation, patient images are acquired using fluoroscopic techniques done in real-time. These images contain both the vessels and the surrounding tissue. To simulate this surrounding tissue, we are using CT data taken from the Visible Man to produce a pseudo-volumetric representation.

Volumetric rendering puts high demands on computer hardware, requiring expensive workstations to achieve interactive frame rates. We have developed a pseudo-volumetric rendering process, taking advantage of the limited degrees of freedom of camera motion in the actual procedure, to allow the user to interactively change camera viewpoint in real-time. We call our approach "x-ray casting" [7]. This method was developed to permit rapid generation of fluoroscopic views as seen through 360° of rotation about the patient, as well as head-to-toe longitudinal camera translation.



Figure 1 Visualization and haptic interface for catheter simulator

A realistic VE simulation requires that there be no perceptible delay between user action and the system's visual and haptic response. A primary goal of our simulation has been to minimize response time by simplifying calculation as far as possible while still providing a credible response to the catheter operator.

For purposes of the simulation the vascular model is defined as a sequence of cylinders or truncated cones defined by the model's nodes and radii at those nodes. The catheter is assumed to move in a straight line when unobstructed and to be deflected when it encounters the walls of the vascular model. In the current model it is assumed that the walls are not deformed by catheter contact.

The wall contact points determine the catheter shape and haptic response as the catheter is guided through the vascular model. When unimpeded its path is straight, and neither its shape nor the response forces are modified. When a collision is detected, or when it slides along the wall, its path is recalculated as a series of overlapping splines proceeding backwards from the tip. During

the recalculation existing contact points may be moved or deleted, and new points may be added. At its conclusion the new haptic force feedback is calculated, and the revised shape is passed to the simulated fluoroscopic display.

The actively controlled electromechanical haptic catheter which serves as the tactile input and output device is unique to this interactive system. Based on the geometry of the patient's anatomy and the mechanical properties and position of the catheter, the computer can calculate what forces and torques the person holding the catheter should experience. The catheter held by the physician is actively driven so as to produce these tactile sensations.

The forces and torques applied to the catheter by the radiologist, along with the current linear and angular position of the catheter, are sent to the simulation model. Knowing the vascular geometry and the catheter's mechanical properties, the simulation sends appropriate data to the visualization and display algorithms and transmits force, torque, and position control commands back to the intermediate control computer.

Cryotherapy of the Prostate Cancer

Prostate cryotherapy is a relatively new procedure for prostate cancer in which the prostate gland is treated in situ by freezing. The freezing and thawing process destroys the prostate glands, which are replaced by scar tissue following the procedure. This is accomplished by inserting several cylindrical cryoprobes into the gland under ultrasound guidance. Thermocouples are placed at strategic locations within and around the gland to monitor the formation of ice crystals around the cryoprobes which occurs when the cryoprobes are activated. The ability of a physician to deliver an efficacious freezing injury is largely dependent on clinical experience and the ability to create an area of treatment known as an 'iceball' that kills the target cancerous tissue without damaging surrounding tissues.

A prostate cryotherapy simulator has been developed to expedite the learning process associated with this technically demanding procedure. Three dimensional ultrasound images of the prostates from real patients are used. The physician can practice prostate cryotherapy in a clinically realistic manner by placing and operating the cryoprobes before actually treating a patient. During a clinical procedure the physician monitors the iceball growth on ultrasound and also uses the temperature measurements from the thermocouples to assess the extent of the freezing injury. A mathematical cryotherapy simulation with verified accuracy is used to determine the temperatures surrounding the cryoprobes during the procedure simulation. Changes that occur in the ultrasound image when ice forms in tissue have been accurately reproduced. Combining this visual feedback with the thermocouple readings, the physician can judge the extent of freeze injury in both tissues targeted for destruction and tissues that must remain unfrozen.

The interface to the system mimics the devices that the physician interacts with in a real procedure including ultrasound display and control, LCD screen for the cryoprobe instrumentation as well as thermocouples, and the control panel for controlling the temperatures of the cryoprobes. In addition, there is a 3D view pane that shows a bird's-eye-view of the prostate, position of the cryoprobes and the thermocouples, and the growing ice balls. This view is not available during a real procedure. This situational awareness is what an experienced surgeon deduces from inputs of the available instruments. However, giving the user this explicit view allows the user to gain an understanding of how to interpret the information he/she is given during the procedure. At the beginning of the simulation, the user selects from a number of case studies to give a rich variety of simulated experiences. A number of metrics can be recorded during the procedure to give the user a feedback on his/her performance.

Figure 2 Cryotherapy Simulator for Prostate Cancer

Ultrasound display and control are shown in the upper-left part of the screen. This display is generated from a cross-section of a 3D ultrasound volume data for the surgery area. The 3D volume data is obtained by a 3D ultrasound device. The cross sectional view is generated according to the control parameters given by ultrasound control user interface. The control for the simulated ultrasound mimics a real transrectal ultrasound device. A physician can switch between



axial and lateral views. The position and orientation of the transducer are controlled by using the slide bars. In addition to the tissue, the inserted cryoprobes are rendered on the ultrasound. Optionally, labels can be shown on the ultrasound to identify the locations of particular cryoprobes. When tissue freezes, the area becomes opaque to ultrasound. The resultant shadows and diffraction is simulated. The virtual ultrasound view is generated in real time [1,2,6].

The purpose of the simulator is to mimic the freezing process of real cryotherapy. In order to achieve this, thermal simulation is performed based on finite difference model. We use three dimensional grid structure to represent the thermal simulation elements. Each element contains current temperature, and interacts with nearby elements by giving and receiving thermal energy. The freezing process begins at the tips of the probes and neighboring elements are frozen as the simulation proceeds. The temperature information of the elements is always available so that it can be given to the user.

The information about the current situation is given to the operator through the ultrasound image. During the simulation of cryotherapy, the ultrasound image is altered in order to reflect the changes made by the freezing process. Iceball regions are identified by the thermal simulation module as being opaque to ultrasound. Ultrasound shadows and reflection effects are added. LCD display shows the current temperatures for all cryoprobes and thermocouples. The current operating modes of the cryoprobes are also provided. The graphs in the display shows the temperature history for the cryoprobes.

Conclusion

Despite the prevalence of surgical simulation systems, very few are actually being used routinely for training. The difficulty is not only technical but in engineering a system that fits the task. In the first simulator describes, we have taken a high-end approach. We have tried to produce a simulator that is capable of reproducing the simulated procedure as accurately as possible. This is an example of a full simulator. One of the disadvantages of this approach is the

cost involved. A special purpose interface device was necessary. The simulation system stretched the limits of the high-end graphics hardware.

In the second simulation system, we have taken the approach that many low-end flight simulators have taken in that we have concentrated on the intellectual learning component and left out the manual dexterity to be learned in actual procedures. This is an example of a part-task trainer. The simulation system has been developed and has gone through several iterations. Preliminary indications are that it is effective in training the user in the techniques and the instrumentation and is an important component in a coherent and comprehensive training program for the procedure.

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