PREOP™ ENDOSCOPIC SIMULATOR: A PC-BASED IMMERSIVE TRAINING SYSTEM FOR BRONCHOSCOPY

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Abstract: The high cost of simulators that offer adequate realism for training has been a major challenge for the simulation community. The cost of the computers alone has been too high for most training institutions to afford. We have met this challenge by developing the PreOp™ Endoscopic Simulator, our second generation of low-cost medical simulators. The PreOp™ system integrates multimedia, 3D graphics simulation, and force feedback technology on a PC. This paper discusses the challenges of this project and the trade-offs and solutions that we developed to overcome them. We discuss our process of analyzing and prioritizing the medical tasks necessary to correctly perform flexible bronchoscopy. In addition, we illustrate how we blended together simulation and multimedia technology to ensure adequate immersion and training efficacy, while keeping the system cost to a minimum.

1. Introduction

The PreOp™ Endoscopic Simulator is a simulation system that trains physicians to perform endoscopic procedures. Examples of these types of procedures are bronchoscopy, flexible sigmoidoscopy, colonoscopy, EGD, ERCP, and ureteroscopy. Flexible bronchoscopy is the first module for PreOp™ that we have developed.

Approximately half a million flexible bronchoscopies are performed annually in the U.S. [11, 10]. This procedure involves placing a flexible fiberoptic endoscope through an patient’s nose or mouth, past their vocal cords, and into their lungs. Indications for flexible bronchoscopy include diagnosis of lung cancer, pulmonary infections, interstitial lung disease, and removal of foreign bodies.

This procedure has an overall mortality rate of 0.1% and a rate of major complications of 1.7% [15]. Major complications include respiratory arrest, pneumonia, pneumothorax, airway obstruction, and severe bleeding. This procedure is technically difficult to learn because of the fractal-like branching of the lungs. It is common to get disoriented as to the exact location of the bronchoscope within the bronchial tree because the lumens of all the segments look similar.

Currently, the most common way to learn bronchoscopy is by practicing on patients. Some teaching programs have latex or rubber models of the bronchial tree, but these are not very realistic and therefore not widely used by the students. The PreOp™ Endoscopic Simulator for Flexible Bronchoscopy provides a realistic training

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environment that allows the student to learn bronchoscopy without putting patients at risk. The student can experience a myriad of complications in a relatively short period of time on the simulator, and can rehearse the appropriate medical responses to these complications before they occur during an actual procedure.

1.1 Previous work

Because of the mostly rigid nature of arthroscopy simulating this procedure has been popular (e.g. [9, 13, 14]). Since most objects in the virtual scene are rigid very little deformation needs to be modeled. Deformation is computationally expensive and having little deformation allows for implementation on low-level platforms. However, force-feedback is more difficult and takes more computational power for rigid objects. This is mainly because the force-feedback needs to be active (push) rather than passive (brake), and the update-rate in the control loop has to be on the order of 300-1000 Hz. As a result, expensive force-feedback devices are used in these systems, and the computational resources saved from the lack of deformation is often spent doing force-feedback.

Surgery in the abdomen probably represents the opposite of arthroscopy. In this case, almost everything is deformable and modeling the deformation is the main focus in the implementation of simulators for these procedures. Examples of work in the abdomen are [1, 6, 7, 12]. Because of the theoretical challenges presented by deformation basic research in deformable models has often used the abdomen as the subject. Examples of basic research in deformable models for surgical simulation are presented in [2, 5, 7, 12].

Other procedures that have been the subject of surgical simulators are sinus-surgery ([8]) and eye-surgery ([16]), to mention a few (see [4] for HT work).

The work presented in this paper is unique because it represents a complete commercially ready system. To our knowledge, although some of the systems described in the literature have been offered for sale commercially, these systems have all been demo-style systems rather than complete systems.

In addition, in this work, we have embedded the simulation into a multi-media environment. Not only does this environment allow the student to practice the procedure. But it also provides the student with pre-procedure guidance, patient data, and videos explaining general aspects of the procedure. After each procedure, the environment captures and presents to the student a comprehensive evaluation of performance.

2. Medical task analysis

The first step in developing the PreOp™ Flexible Bronchoscopy module was to perform a task analysis. The medical procedure was broken down into a series of basic steps. Each step was evaluated to determine the most effective training mode: 3D graphics simulation or 2D multimedia (text, illustrations, photographs, or video). The pre-procedure steps (e.g., obtaining patient consent) and post-procedure steps (e.g., completing the proper paperwork) are primarily cognitive and are therefore presented in video and text format.

The actual simulation part of the training system begins when the user inserts the proxy bronchoscope into the virtual patient’s nose. At this point the user can navigate the bronchoscope through the patient’s nasal passage, upper airway and into the tracheobronchial tree. The endobronchial view is displayed on the monitor, just like in an actual endoscopy suite. The user feels the appropriate forces based on their actions with the bronchoscope and their location in the virtual bronchi. For example much resistance is encountered as the physician inserts the bronchoscope through the patient’s nasal passage, but this resistance decreases substantially as the scope enters the patient’s throat.

The user can inspect all segments of both lungs, as well as perform procedures such as a bronchoalveolar lavage, forceps biopsy, or needle biopsy. The virtual patient will respond to the user's actions in a physiological manner. For example, the patient will cough when the scope collides with the bronchial walls if the user has not instilled the proper amount of lidocaine.

3. Methods

3.1 Architecture

One of the major design goals was to embed the simulation into a multi-media environment. Since the preliminary design called for a large portion of the system to be 2D based desciption, introductions and videos, it was natural to try to leverage the power of existing multimedia authoring tools for this part and focus the development on the actual 3D graphics simulation.

To accomplish this goal the design had to be modular and based on a component technology that would allow the graphics simulation to interface seamlessly with the multimedia part of the system. Finally, the requirements called for the system to be developed on a PC.

In the end we selected a commercially available multimedia authoring tool and chose to develop the graphics simulation as an ActiveX component that would allow it to be used as an extension to the authoring tool. Using the ActiveX component technology allows the graphics simulation to be a plug-in for the multimedia tool. Since ActiveX is a general standard, the graphics simulation could also be used as a plug-in for any other ActiveX-ready software package. One of the more intriguing examples would be to plug the graphics simulation into a Microsoft Power Point document thus allowing us to make a presentation where one of the slides would run the simulation!

3.2 System overview

An overview of the system is presented in figure 1. The graphics simulation is shown in the right connected via an ActiveX interface to the Multimedia Interface (GUI) that embeds it. Examples of the multimedia interface are shown in figure 2.

The Multimedia Interface is connected to a user manager component. The user manager is used to access security and performance information about the students stored in the User Database. In addition, a Multimedia Database is attached to the interface (see figure 2). This database contains comprehensive information about the different procedures that the system can train. For each procedure the database contains general

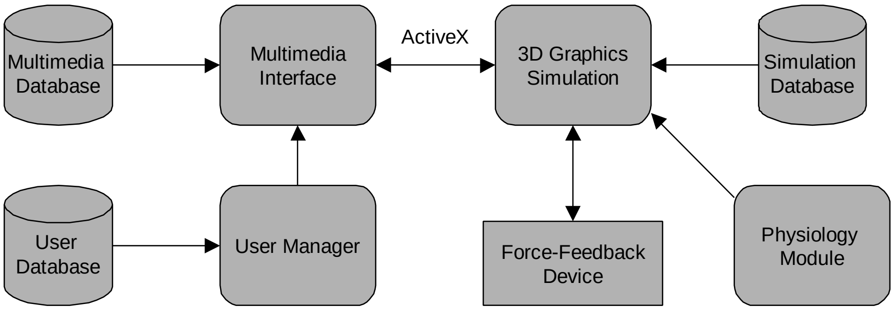


Figure 1. System overview diagram.

Figure 2. Multimedia interface

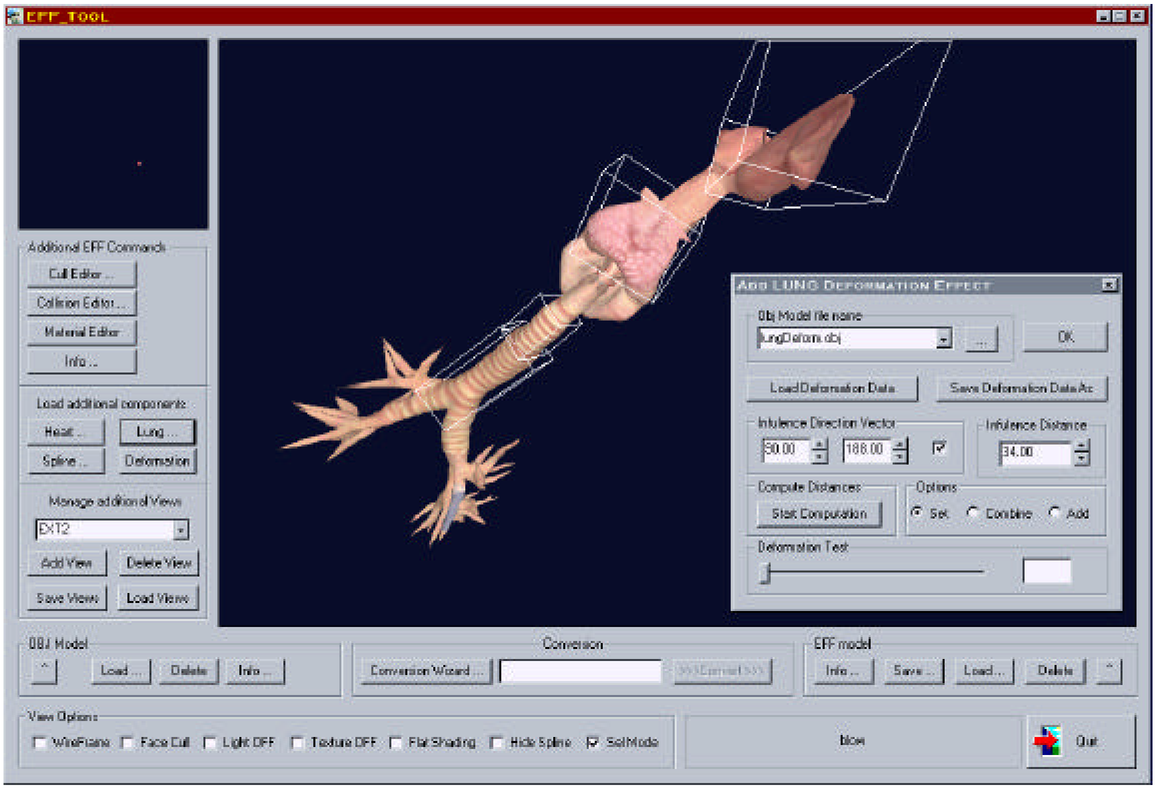
instructions, patient data, images, videos and explanations used during the preparation for the procedure. Finally, each case of a procedure is linked to a section in the Simulation Database which is used by the 3D Graphics Simulation to run the simulation. The Simulation Database contains all the information needed to start and run a 3D graphics simulation. For each case of a procedure it stores all the information that is needed for the simulation. This information includes geometric and physical descriptions of the anatomy, and pathologies associated with the anatomy. In addition to the anatomy, pre-computed information used for simulating the navigation of the flexible scope is stored along with geometric and functional descriptions of the tools used in the procedure.

The Force-Feedback Device is attached to 3D Graphics Simulation and provides the main user-interface to the simulation. The device captures the movement of the flexible endoscope and tools, such as a biopsy needle, that are used in the working channel of the scope handle. In addition it provides passive force-feedback to the user. Passive force-feedback was chosen mainly to minimize the cost of the system. But in our preliminary study of the procedure we also determined that the potential benefits of an active force-feedback device would be minimal. Most force-feedback in flexible bronchoscopy is the result of frictional forces and these are easily represented using passive forces.

Finally, the Graphics Simulation is connected to a Physiology Module. This module contains models of the heart and lung of the patient. The module provides data to control breathing, coughing, heartbeat, and other vital signs that influence movement of structures in the anatomic models or are shown on monitors attached to the patient (e.g. ECG). The modular structure of the design allows us to replace this module with more advanced models of the patient-physiology in the future. The current models are sufficient for the simulation. But it would be interesting to connect the system to external systems that could complement the simulation. We are currently exploring such a link-up with the anesthesiology simulator developed at the University of Florida.

3.3 Model development

Each case entry in the Simulation Database is compiled from data from a large number of sources. To store this information we have developed a proprietary database format and a Model Editor that allows us to compile all the necessary information (see figure 3). This software tool reads graphics files and other data files and allows the user to edit the information to make the integration seamless. In addition, the tool is also used to add information about deformations, navigation, and drawing details to the database. Basic anatomic models are extracted from CT or RGB images using the Mvox software [3]



Obj Model file name: LungDeform.obj

Influence Direction Vector: 50.00 188.00 ☑

Influence Distance: 34.00

Compute Distances

Options: ● Set ○ Combine ○ Add

Deformation Test

Manage additional Views: EXT2

View Options: ☐ WireFrame ☐ Face Cull ☐ Light OFF ☐ Texture OFF ☐ Flat Shading ☐ Hide Spline ☑ SelMode

Figure 3. Model editor user-interface.

3.4 Deformation

The flexible bronchoscope is modeled using a physical model of the tip combined with a kinematic model of the body of the scope. This allows the user full freedom in moving the scope within the lungs, and at the same time is computationally efficient.

The lungs of a patient move because of breathing, heartbeat, vocal cords movement and occasional coughing. To simulate these deformations each model contains information about elementary movement that these physiological effects can produce. These elementary deformations are combined during run-time to produce global natural deformations. The elementary deformations are sometimes complex and are developed using a graphical modeling tool and combined and positioned in the Model Editor. See figure 4 for an example of deformation of the vocal cords.

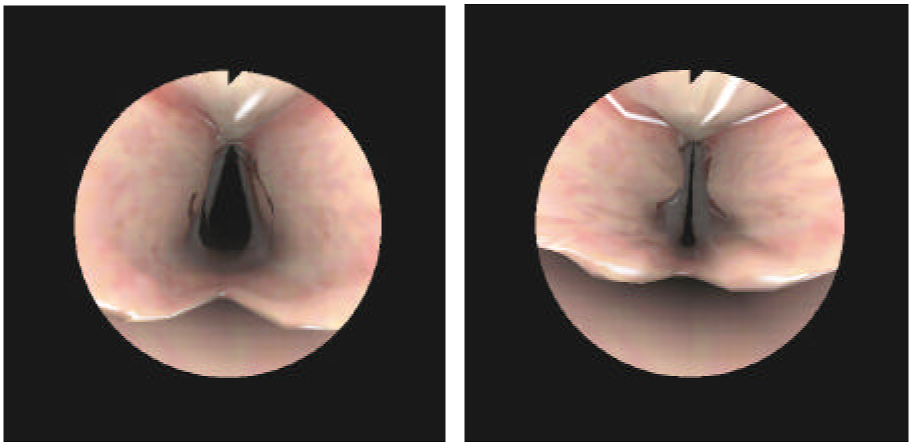


Figure 4. Example of deformation of the vocal cords.

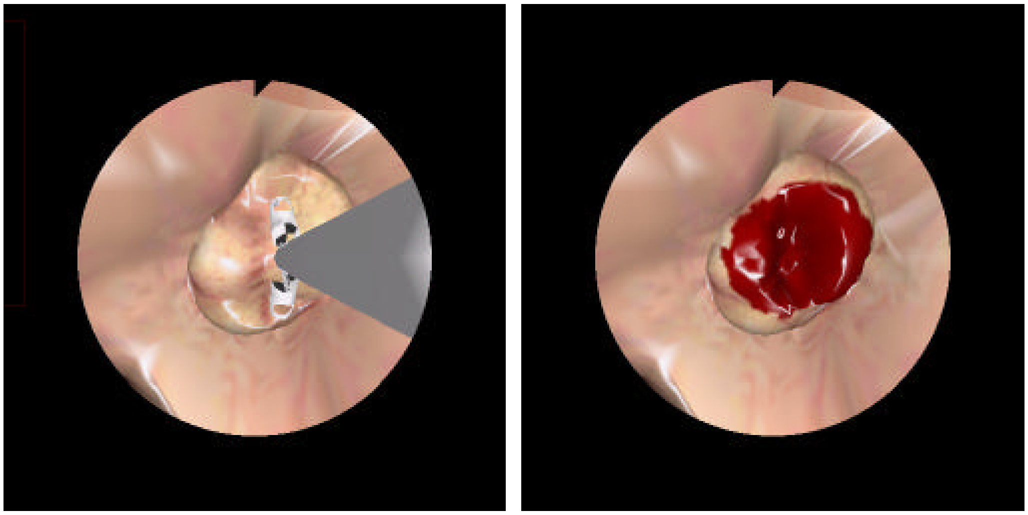


Figure 5. Biopsy of a polyp. Left: Before with deformation from tool. Right: After with blood.

3.5 Visual effects

In a flexible bronchoscopy procedure a range a things happen that can be classified as visual effects. These are graphical effects that do not have any significant important to the actual procedure. But they add visual and functional realism to the system. We have implemented several visual effects in the system.

During traversal of the bronchial tree the endoscope will occasionally touch the walls. When this happens the view is temporarily obscured and instead shows a redish blur caused by light from the scope reflected from the wall of the bronchi. After the user pulls the scope away from the wall mucous or other secretions will remain on the scope, partially obscuring the view. These secretions can be removed by either touching the wall again, by suction, or by spraying saline through the working channel. We have modeled the entire sequence of events with visual effects.

Another result of touching the walls is that the patient starts to cough if the part of the bronchial tree, that the scope touches, has not been anesthetized. To anesthetize the patient the user can spray lidocaine into the current branch and the system shows the visual effect of this. In addition, the system calculates the flow of the lidocaine down through the branches of the tree and accumulates the amount of lidocaine each branch receives. The amount/probability of coughing is determined based on the amount of lidocaine a branch has accumulated.

3.6 Biopsy

Several different procedures have been implemented in the system. One of the more interesting is biopsy of a polyp. Polyps are attached to the bronchial tree as small bumps in the surface, some larger than others . These bumps are incorporated into the geometrical model as general pathologies and the model is refines around a polyp to ensure that the visual result is satisfactory even when the user comes close to it.

A biopsy is performed using a biopsy tool inserted in the working channel of the bronchoscope handle. When the user inserts the tool a graphics model of a fully functional biopsy tool appears in the view of the scope. Using the tool the user can deform the polyp and subsequently grab part of the polyp and pull away a tissue sample.

After a biopsy a bloody gap is left in the polyp and blood is spurted onto the inner surface of the bronchi and onto the scope. The user often needs to use spurts of saline and/or suction to remove the blood from the scope view. See figure 5 for an example.

4. Conclusion

The system presented here has been shown to several doctors in the field of flexible bronchoscopy and the response has been very positive. The visual realism of the 3D Graphics Simulation and the convincing Force-Feedback Device, coupled with the comprehensive and realistic medical content, provides a completely new level of simulation. We feel that it is fair to say that this system is the first fully 3D Surgical Simulation system with realistic commercial and medical application.

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