Training Environment for Inferior Vena Caval Filter Placement

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Abstract. This paper describes a Virtual Environment system designed to aid in training interventional radiologists in inferior vena cava filter placement. It is being developed as part of a VE simulator for a number of surgical and interventional radiology procedures at the Laboratory for Advanced Computer Applications in Medicine at the George Washington University. In this procedure a filter is placed in the inferior vena cava to prevent blood clots from the lower portion of the body from reaching the lungs and causing a pulmonary embolus. The simulation is designed to provide both tutorial and testing modes for the filter placement procedure.

1. Introduction

Recently, Virtual Environment (VE) technology has been applied for simulating a variety of surgical and interventional radiology procedures. 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.

One of the reasons that VE 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 VE with limited interaction modes.

The Laboratory for Advanced Computer Applications in Medicine (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 VE simulator for a number of surgical procedures. Currently we are involved in developing a VE-based trainer for inferior vena cava filter placement. This paper describes the system and its application in the field of interventional radiology.

2. Purpose of work

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.

The simulation environment that we are developing is designed to assist the training as well as testing of interventional radiologists in this procedure. Once the filter is placed it is essentially permanent. It can only be retrieved by having the patient undergo a massive abdominal surgery. The exact location of the filter within the IVC is critical. Therefore, the placement has to be highly accurate. The deployment of the filter involves many steps and there are currently no available methods to practice deployment of these filters.

We believe that a simulator should be coupled to a complete training environment for it to be effective. To this end, we have encapsulated the simulation system within a comprehensive training environment that is designed to be a tutorial as well as a testing environment for a variety of scenarios. In addition to producing a specific training environment, we believe that individual technical building blocks as well as the approach that was used to integrate them in this work can be applied to a variety of catheter trainers in particular and surgical trainers in general in the future.

3. Methods

The training environment has five components: building the geometric data structure, visualization, simulation of the tissue with the instruments, interaction with the simulation through a haptic device, and a tutorial/testing system to guide the user through a number of scenarios and to gather metrics for evaluating the performance of the user.

3.0 System overview

The system hardware consists of an SGI Onyx RE2, the catheter interaction device, and a PC which acts as its local controller and communications link (figure 1.) The simulated fluoroscopic view of the patient and the tutorial environment are displayed by the SGI. The user interacts with the tutorial using a mouse and manipulates the catheter with the haptic device.

In figure 1, patient data acquired from MRI scans is processed on the SGI to create two databases. A segmentation process (section 3.1) extracts a blood vessel structure. An x-ray casting process (section 3.2) prepares a representation of the overall anatomy. The SGI also maintains a current model of the inserted catheter. The simulation (section 3.3) updates this model as the user inserts and twists the catheter through the haptic interface (section 3.4.) 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 on the SGI (section 3.5.)

Localizing a portion of control over the interface device on the PC facilitates smoother and more rapid response to user actions. It also allows data flow between the device and the SGI to be minimized by suppressing redundant or unnecessary input.

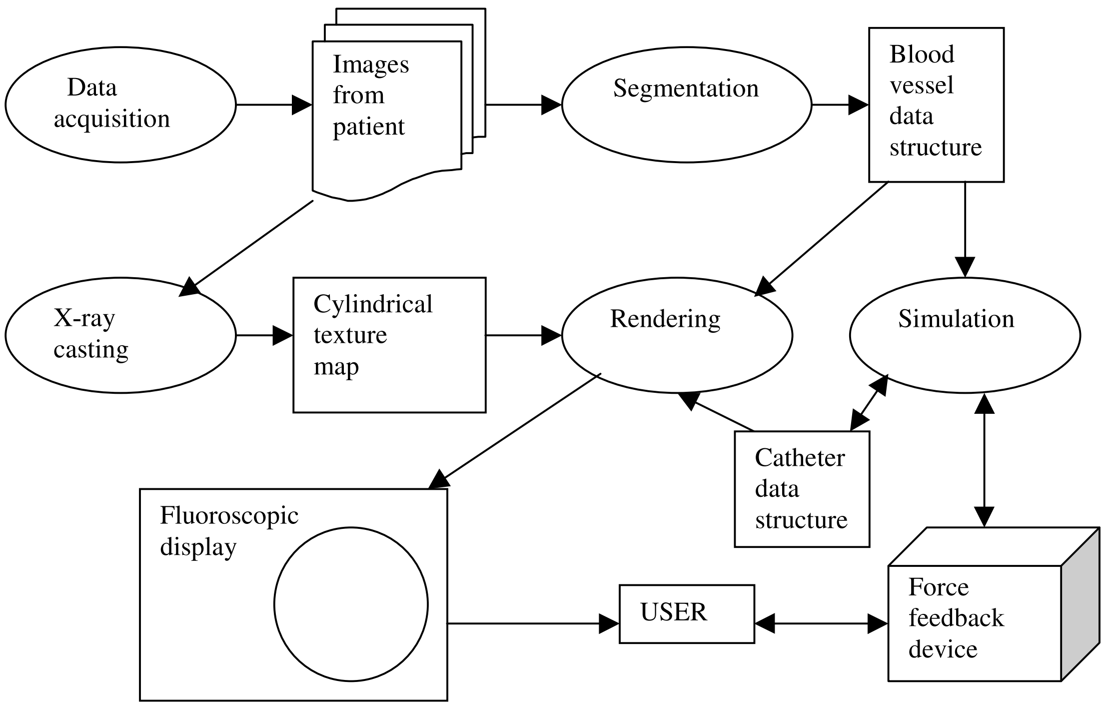

Figure 1. Virtual training environment architecture.

3.1 Vessel data structure

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 [1] 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 visualization engine of our system interprets the abstract representation and reconstructs an image of the vessel when contrast agent is present. Collisions between the catheter and the vessel are detected through mathematical functions based on the information contained in the abstract model. Finally, the simulation uses physical principles to compute the forces generated by the catheter's interaction with the model.

3.2 Visualization

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" [4]. 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.

The injection of opaque contrast agent into the vein is modeled using a particle system [2, 3]. A cloud of particles is released upon request from the tip of the catheter. The cloud's location is recorded at discrete time intervals as it travels towards the heart, and these images are displayed with the surrounding tissue representation. This hybrid approach, combining ray-casting and particle systems, allows us to more realistically and efficiently model the dynamic nature of the human body.

3.3 Simulation

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.

As the tip encounters branches in the vascular model, its path is projected. If it passes through one of the branches without collision, that branch is chosen. If collisions occur in all branches, a choice is made based upon the tip rotation and the relative angles of the branches. This permits the operator to guide the catheter through any desired path.

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 catheter operator applies two types of force, linear and rotational, and receives force feedback simulating the interaction of the catheter with the vascular model. For each type the haptic feedback felt through the simulator has two components; restitutive and frictional force. Restitutive force, $\mathbf{F}_R$, is generated when the catheter is forced to deform by an obstruction and attempts to return to its natural conformation. Frictional force is experienced at each point where the catheter encounters the arterial wall. It is proportional to the deformation of the catheter segment at that point. A total static frictional force, $\mathbf{F}_F$, is calculated as the sum of the forces at the individual points.

$\mathbf{F}_R$ and $\mathbf{F}_F$ for both linear and rotational force are returned to the PC controlling the simulator by the simulation model and retained there. To minimize response time, as long as the linear (or rotational) force exerted by the catheter operator remains within the range $\mathbf{F}_R \pm \mathbf{F}_F$ an equal opposing force is applied to the simulator by the PC and control remains at the local level. When the applied force goes outside of this range the PC continues to respond with the limit value force, but permits motion, and the new data is sent to the simulation model for recalculation.

The current catheter model is an oversimplification of the real catheter used. As experience is gained, a catheter model incorporating varying thickness and mechanical properties should be introduced for more realistic navigation. Varying catheter motion due to blood flow and systolic action can also be included.

3.4 The haptic interface device

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.

Where the catheter is blocked by collision with a vessel wall the person pushing on the catheter feels an increased resistance. When the catheter is twisted to steer the tip into a branch of the artery, the display shows the new conformation and the user of the system feels the change in position and force.

As the interventional radiologist working with the device pushes, pulls, or twists on the end of the catheter, force and torque sensors attached to the catheter measure the stresses being applied. This force/torque sensing module contains a system of strain gages arranged so as to uncouple and orthogonalize the force and torque effects. Forces or torques sensed by the strain gages are converted into electrical signals which are transmitted through slip rings, amplified, and finally converted from analog to digital form.

The force and torque sensing module attached to the end of the catheter within the simulated patient rides on an actively controlled torsional drive which controls the angular rotation of the end of the catheter. This twisting mechanism rides, in turn, on a servo motor controlled linear carriage assembly. Shaft position encoders on both the torsional and linear servo motors determine the actual linear and angular positions of the catheter tip and transmit this information to the control computer.

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.

The design of the system allows the control computer to receive one of two kinds of command information back from the modeling computer. It might either be told to correct the forces or torques to some calculated “setpoint” values (as determined by the real-time simulation running concurrently) or else it might be told to correct the linear or angular position of the end of the catheter. In either case, the correction is made by the servo motors pushing, pulling, or twisting on the end of the catheter till the error between the command value and the actual value is driven towards zero.

A dynamic model of the physical interaction device resides within the control computer. This model of the "plant" determines the needed corrective action. The feedback loop then drives the linear and rotational servo motors so as to eliminate residual errors in force, torque, or position.

By having an active catheter simulation system rather than a purely passive braking device we eventually hope to be able to accurately model fine nuances such as the slight "springback" which a radiologist might experience. This might occur, for example, as the tip of the catheter unsnags when it enters a branched vessel and residual loops or kinks in the catheter suddenly straighten out. We might also be able to model subtle phenomena such as the effect of a catheter touching the pulsating wall of the heart.

3.5 User interaction

The user session has two modes; tutorial and testing. The progression of the two modes is similar. In the tutorial mode, the user is guided through a procedure while relevant online guidance and commentary are displayed. In the testing mode the user will perform a procedure on the basis of previous training, with scoring and commentary being displayed at the conclusion.

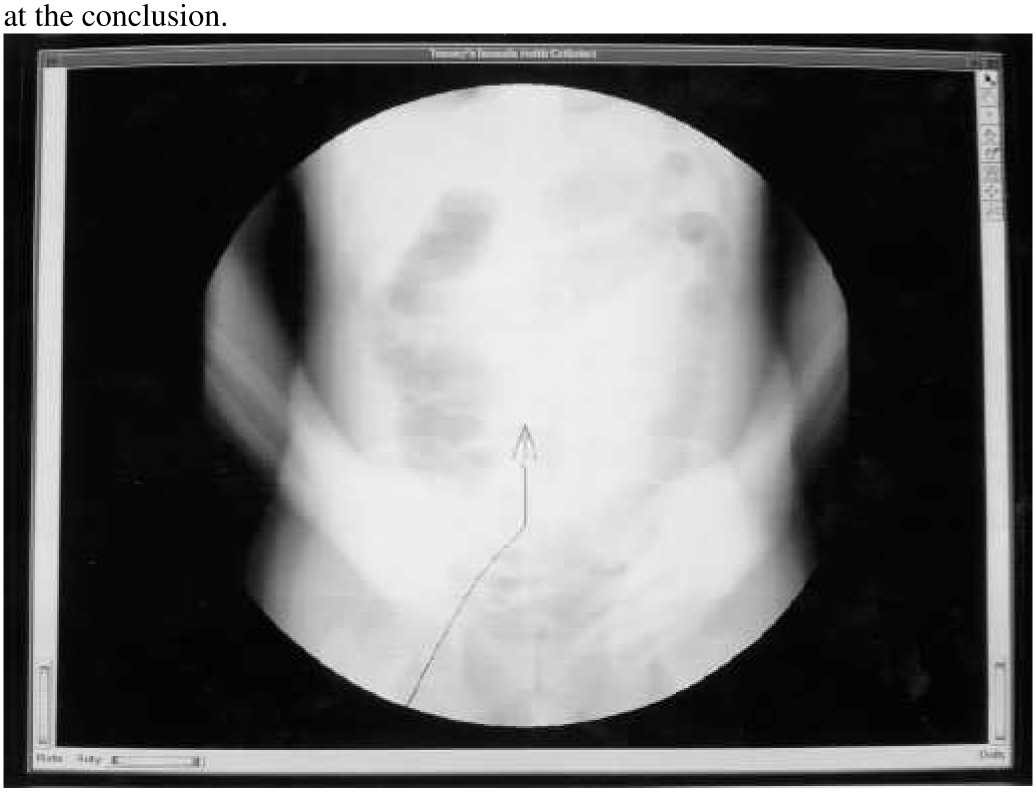

Figure 2. Simulated fluoroscopic view with catheter and filter.

In either mode the user is presented with a randomly selected case at the beginning of the session. A simulated fluoroscopic view of the patient is then displayed along with pushbutton menus representing various choices and actions. Based upon the case data, the user must make a series of decisions beginning with the suitability of the procedure for the patient presented. If the decision to proceed is made, then an insertion site for the catheter must be selected. Currently six sites may be chosen; right or left femoral, jugular or basilic veins. Following puncture of the vein, the user should inject contrast agent to check for exiting clots. The contrast agent is displayed an opaque cloud travelling through the venous system in a sequence of still images at discrete time intervals. As in the operating room, these images are recorded and may be recalled for reference.

After an appropriate site is chosen, the user selects a catheter type and inserts it. As the catheter is inserted, its image is seen on the fluoroscopic display. Contrast agent is again injected in the proper region to find the renal veins. A recalled image is chosen and used to measure the diameter of the vena cava. The user is graded on placement and accuracy of the measurement, and a preselected figure for the patient is given. The catheter is then withdrawn.

One of four filter types is chosen and inserted with the catheter. Its image is seen at the end of the catheter (Figure 2.) Contrast agent images are again used to select a site for placement and to check for proper placement. At the conclusion a summary of the procedure with times and commentary is displayed.

4. Results

We envision three phases in the development of an effective training environment: building the simulator, building the training/testing environment, and testing the effectiveness of the system. As of this writing, we have completed the first two phases. We plan to start subject studies using the environment technical contribution of this project as systematic integration of a number of separate technical solutions into a coherent system. Aside from the technical challenges of building such a simulation environment, the biggest challenge we faced was putting together an interdisciplinary team from a variety of fields to work coherently on a single project.

References

[1] Lorensen, W., and H. Cline. Marching Cubes: A High Resolution 3D Surface Construction Algorithm. Proc. SIGGRAPH 87, pp. 163-169, 1987.

[2] Reeves, W., Particle Systems – A Technique for modeling a Class of Fuzzy Objects. ACM Transactions on Graphics, 2(2); 359-376, 1983

[3] Tonnesen, D., Modeling Liquids and Solids using Thermal Particles. Graphics Interface '91, pp.255-262, 1991.

[4] Park, Y, R. Lindeman and J. Hahn, X-ray Casting: Fast Volume Visualization Using 2-D Texture Mapping Techniques, The Seventh Annual IEEE Visualization Conference, 1996.