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A "smart" haptic simulator will help novice surgeons learn from the pros

DIANA PHILLIPS MAHONEY

Computer-based surgical simulation has for years been one of the hottest topics in virtual-reality research. Not only does the technology have the potential to revolutionize the teaching and practice of medicine, but it also encompasses some of the most pressing computer visualization challenges of the day: real-time interaction with complex 3D datasets, photorealistic visualization, and haptic (force-feedback) modeling. What's more, it requires that all of these be achieved in the same application.

Few other VR applications are subject to such stringent constraints. Often, in other applications, one or more of the technical considerations mentioned above can be sacrificed for the sake of another. For example, if real-time interaction is a priority, it may be achieved at the expense of photorealistic images or sensitive force feedback and vice versa. In contrast, for a surgical simulation to be useful as a training and planning tool, it must answer to a higher technical call.

Roger Webster and Randy Haluck know this, and are building their surgical simulation system accordingly. Webster, a computer scientist at Millersville University of Pennsylvania, and Haluck, director of minimally invasive surgery at Penn State's Hershey Medical Center, have joined forces to develop a surgical simulator that will not only enable real-time interaction with photorealistic 3D imagery and sensitive touch feedback, but will also measure the skills of expert surgeons relative to novice surgeons, providing the novice with an objective means of identifying areas of strength and weakness.

The simulator will also be used to compare skills measured during live surgery with those obtained from a virtual procedure to test whether there is indeed a technology transfer between the two. "The general assumption is that virtual surgery simulation is beneficial. It seems intuitive, but it has yet to be proven, so we're setting out to do that," says Webster.

With funding from the medical center, the researchers have begun developing a computer-based simulation system representing a range of surgical procedures. An initial component is a proof-of-concept application that lets surgeons and medical students, via real-time visual and haptic interaction with a photorealistic model, practice suturing. The virtual environment for this application comprises polygonal models of patient anatomy. The skin covering the models is a grid of dynamic vertices texture-mapped with a photograph of an actual wound. To interact with the digital model, users manipulate physical suturing tools that are attached to a haptic device (the Phantom from SensAble Technologies), while viewing virtual counterparts of the same tools on-screen. The virtual environment was programmed using EA/Sense8's WorldToolKit.

To model the sensations related to the "touch and feel" of the virtual objects in the environment, the researchers used SensAble's GHOST software development kit. To simulate the impact on the skin and underlying tissue of pushing, pulling, cutting, and so forth, they developed a basic mass-spring model, through which the skin is approximated to a deformable surface made up of a network of masses and springs. The skin deforms relative to the weight, or pressure, applied to the springs through the surgical tool. The software calculates the contact forces in the soft tissue surrounding the wound and applies the appropriate forces to the user through the Phantom. The resistant forces change when the needle is inserted into the virtual skin and when it's pushed through the soft tissue. The software graphically shows the deformation of the virtual skin as well.

The skills-assessment capability is also based on a mathematical model. To quantify surgical activity, the researchers are creating a software implementation of the finite-state machine model. With this, a range of surgical states and transitions between states will be tracked. The states include idle, grasping, spreading, pushing, sweeping, and lateral retraction, as well as numerous combinations of these, such as grasping/pulling, pushing/sweeping/spreading, and so forth. In the virtual environment, these states will be tracked directly from the motions of the Phantom. In physical surgery, the surgeons' motion will be tracked by an electromagnetic position and orientation sensor system and the data will be input to the software for motion analysis.

"The initial state is the idle state, where nothing is happening. When the user starts the procedure, he or she transitions to other states, like grasping, spreading, or pushing," says Webster. "All of these, and combinations of these, will be modeled as the user progresses from one state to another."

The goal, says Haluck, is to be able to quantify the nature of the states through which an expert surgeon progresses in performing a suturing operation. "We want to know how long the expert surgeon spends in each of those states so we can compare that against novice surgeons to see whether they go through the same states and transitions or different ones, and how long they spend at each state." For example, novice surgeons might spend an inordinate amount of time in the idle state, thinking about what to do next, or they may be pushing and grasping when, based on the expert's approach, they'd be better off pulling at that point in the suturing process.

Such information can be an invaluable training tool, says Haluck. "We can show the novice surgeon the different states and how long the expert spent in each of the them. And based on the numbers, we can say something like, 'You're spending too much time in the grasping and pulling state after you have been in the lateral retraction state.' The benefit is that it will give concrete skills-assessment feedback, rather than someone saying, 'I don't like the way you're suturing.'"

Fine-tuning the Model

The project is still in the investigative stage, notes Webster, adding that there are a number of daunting technical and conceptual hurdles yet to overcome before the simulator is deemed surgeon-ready.

The first and most significant of these is fine-tuning the haptic model for soft-tissue deformation. "This is one of the more difficult problems in virtual surgery. There are a number of classic computer graphics things we can do to make the simulation look more realistic, but in terms of making it feel more realistic, we're just starting to scratch the surface," says Webster. "In our research, we're trying to invent an engineering model of how tissues and organs should feel. We need to tweak the model to get more accurate resistant force calculation algorithms."

Haptic accuracy is mission-critical, says Haluck. "Everything we do as surgeons relies on force feedback. Organs and blood vessels respond to manipulation and tissue handling. And the forces involved are essential to identifying pathology, determining tumor boundaries, and assessing how the repair is going. We have to have the same sensory involvement in a simulation."

Some of the other obstacles the researchers face relate to the field of computer-based surgical simulations in general. "The whole notion of computer-based surgical training outside of the actual operating room is underappreciated," says Haluck. "For example, the NIH seems to be focused on molecular-level research, but when it comes to education and training, funds are limited." Additionally, he says, there is a resistance to change within the surgical community. "There's a necessary time commitment to training outside the operating room. The thought of fitting in extra hours for simulation training has little appeal to a surgical resident who is already pulling 36-hour shifts. A surgeon beyond residency training in a busy practice may react similarly."

Not making the time, however, is an increasingly dangerous pattern, particularly in these days of rapid-fire high-tech advances that are meant to help save lives. "Every day, new technology is being tossed at us. In the good old days, you could train by learning to cut, sew, and tie, and those skills would get you through an entire career. Today, especially as computer power increases, we're faced with new technology all the time--different visualization techniques, and different skills requirements, such as laparoscopic surgery and robotic surgery," says Haluck. "The technology is coming so fast that the opportunities for complete training are limited. Obviously, research into better teaching methods and better skills assessment methods will make the transition safer. A critical component of that is computer-based simulation."

Eventually, the haptic simulation system will serve as a teaching tool for Penn State's College of Medicine and other medical schools. Information about the system is available on the project Web site at <http://cs.millersv.edu/haptics/index.html>.

Diana Phillips Mahoney is chief technology editor of Computer Graphics World.

Computer Graphics World October, 1999