Open Surgery Training Simulator

Using Haptics and Augmented Reality Technologies

BY

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THESIS

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To my dearest Parents,
for being such an inspiration to me.

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CJL

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LIST OF ABBREVIATIONS

3D	Three dimensional
AANS	American Association of Neurological Surgeons
AR	Augmented Reality
CAVE	Cave Automatic Virtual Environment
CRT	Cathode Ray Tube
CT	Computed Tomography
DLP	Digital Light Processing
DOF	Degrees of Freedom
EVD	Extra-ventricular Drain
FPS	Frames per Second
FOM	Foramen of Monro
FOV	Field of View
HMD	Head Mounted Display
GPU	Graphics Processing Unit
ICP	Intra-cranial Pressure
ICU	Intensive Care Unit
LCD	Liquid Crystal Display
MRI	Magnetic Resonance Imaging
SXGA	Super eXtended Graphics Array
VPS	Ventriculo-peritoneal Shunt
VR	Virtual Reality
VRML	Virtual Reality Modeling Language

SUMMARY

This thesis focuses on the research and development of an Augmented Reality (AR) system to simulate open surgical procedures. As a proof of concept, a neurosurgical procedure called ventriculostomy is simulated. This surgical procedure consists of the insertion of a catheter in the brain ventricles for draining excess spinal fluid and reducing intracranial pressure. While performing the surgery, neurosurgeons must rely on their fine eye-hand coordination and sense of touch to properly orient and introduce the catheter, as a subtle puncturing sensation is felt when the catheter cannulates the ventricles.

Traditional Virtual Reality (VR) devices are not appropriate for haptic applications because they suffer from occlusion of the virtual 3D objects if the haptic device is located in front of the screen. AR devices, instead, use a translucent mirror to combine virtual and real objects in a common workspace and, therefore, are more suitable to be combined with haptics. However, certain limitations of existing AR devices, such as low visual acuity and poor graphics/haptics collocation, prohibit the implementation of a realistic and useful open surgery simulator.

This work consists of the design and development of a novel haptics-based AR system called *ImmersiveTouch*®, as well as the implementation and validation of a new high-fidelity ventriculostomy simulator that can help trainees to develop the tactile and psychomotor skills required to perform a ventriculostomy. As an interdisciplinary project between the Dept. of Mechanical and Industrial Eng. and the Dept. of Neurosurgery at UIC, the ultimate goal of this doctoral dissertation is to provide an interactive educational instrument to better train medical residents, allowing them to become proficient prior to working with real patients, unrestricted by time and patient safety constraints.

1. INTRODUCTION

Mastery of the surgical skill-set involves many hours of supervised, intra-operative training. However, convergence of political, economic and social issues has limited surgical resident operative exposure. Most importantly, patient safety and procedural efficacy must never be sacrificed for educational purposes (Leach, 2005). This creates a dilemma for surgical educators who must balance their clinical duties with their responsibility to educate the next generation of surgeons.

Ideally, the student should be able to acquire the anatomical knowledge and psychomotor skill-set and "jump-start" the learning process before performing a procedure on a live patient. Traditionally, anatomical knowledge pertinent to a surgical procedure is imparted first through textbooks and atlases. Nevertheless, these techniques often fall short of the goal of imparting the full procedural tactile and psychomotor skills. Animals and cadavers have been used to acquire these skills. However, animals do not have the same anatomy as humans, they are expensive, and they present tissue degradation problems that make them not reusable. In addition, ethical issues arise. Cadaveric dissection provides the most realistic interaction with human anatomy outside of the operating room (OR), but cadavers are unable to provide the same physiological response as living patients. On top of that, the cost and labor involved in creating and maintaining such a facility are not within the reach of all training programs (Strauss et al., 2005).

1.1 Medical simulation

In the last decade, medical simulation has become a valuable learning and practicing tool for acquiring skills that were, until recently, performed by practice on laboratory animals, cadavers and even on living humans. Sophisticated physical manikins, such as the Blue Phantom™, have been used to simulate many surgical procedures in a broad spectrum of specialties. However, manikins do not provide correct human anatomy, are generic (not patient specific), and are unable to dynamically modify the simulated physiological response. A better alternative to manikins are computer-based surgical simulators, which use virtual 3D replicas of a real patient and can simulate different physiological responses, allowing to train medical professionals without compromising patient safety.

Furthermore, the use of computer-based medical simulators has proven to increase patient safety and reduce risks associated with human errors in hospitals by allowing medical students to develop skills more efficiently in a shorter period of time. Previous studies (Rowe et al., 2000) (Datta et al., 2001) (Wong et al., 2001) indicate that training on Virtual Reality (VR) simulators has significantly improved skills and performance of students when compared to those individuals not trained on these devices.

Computer-based surgical simulation systems can be classified into 3 categories: simulators for needle-based procedures, simulators for minimally-invasive surgery, and simulators for open surgery. Due to the fact that open surgeries require the surgeon to have direct visual and tactile contact with the patient, as well as large freedom of motion around the patient compared to minimally invasive procedures, they are much more difficult to simulate. “Open surgery remains the holy grail of surgical simulation”, as it has been stated by Liu et al. (2003).

Among all open surgeries, neurosurgical cranial procedures in particular lend themselves to VR simulation. Anatomical relationships within the skull are generally fixed and respiratory or somatic movements do not significantly impair imaging and rendering. The same concerns that make cranial procedures so ripe for intraoperative navigation also apply to virtual operative simulation. On top of that, the existence of so many cerebral structures allows little room for error, making the need for skill-set acquisition prior to the procedure much more significant.

Recently, interactive neurosurgical simulators have proliferated as computing power has increased. Interactive platforms have been employed to better demonstrate complex anatomical relationships (Henn et al., 2002) (Spicer et al., 2004). (Panchaphongsaphak et al., 2005). Stereoscopic visualization and haptic feedback have been employed for a variety of neurosurgical simulators with application to laparoscopic, endoscopic, and microsurgical training (Bernardo et al., 2003) (Brown et al., 2006) (Cusimano, 2003) (Krombach et al., 2000) (Riegel et al., 2000) (Rowe, 1996). Often, these simulations can import patient-specific data and act as a form of “operative rehearsal” (Kikinis et al., 1996) (Auer and Auer, 1998) (Kockro et al., 2000) (Rohde et al., 2000) (Spicer and Apuzzo, 2003).

1.2 Motivation for ventriculostomy simulation

Ventriculostomy is likely the first procedure that a young Neurosurgery resident will learn and employ on a regular basis. While faculty or senior residents may proctor early cases, the high volume of demand for the procedure means that most residents must become proficient very early in their training. In an ideal world, the resident would understand the proper techniques and "feel" of the procedure before performing one on a live patient.

Currently at the University of Illinois Medical Center, junior residents watch just 2 or 3 ventriculostomy cases before they perform the procedure on their own (under supervision). During the first two years of residency at UIC, residents perform about 300 cases per year in live patients. Due to the procedure's high occurrence rates and possible risks associated to human errors, it is necessary to provide residents an effective training simulator that would result in increased patient safety and procedural efficacy.

Given the current pressures impacting neurosurgical education, the combination of Augmented Reality, 3D stereoscopic visualization, and haptic technology may offer the possibility of improving the current way Neurosurgery residents acquire certain technical tactile and psychomotor skills needed to perform a ventriculostomy. This applies not only to the training of novice neurosurgeons, but also those maintaining or recertifying their surgical skill-set. This work is, hopefully, a step forward to a better educational process and a highly improved patient safety.

1.3 Organization

This Ph.D. dissertation is organized in nine Chapters. Chapter 2 presents a brief overview of state-of-the-art Haptics-based Augmented Reality systems exposing their advantages and disadvantages in the context of surgical simulation. Chapter 3 gives background information about this particular neurosurgical procedure and the existence of earlier ventriculostomy simulators. Chapter 4 describes the hardware design of the *ImmersiveTouch*® simulation system. Chapter 5 explains how the new ventriculostomy simulator is able to help Neurosurgery residents to develop both eye-hand coordination and sense of touch required for the procedure. Chapter 6 illustrates the software design and implementation of the *ImmersiveTouch*® ventriculostomy simulator, followed by Chapter 7, which introduces a new parallel algorithm for real-time deformation of elastic human tissue on the Graphics Processing Unit (GPU). Chapter 8 presents the results of four validation experiments conducted to evaluate the usefulness and potential of the new high-fidelity ventriculostomy simulator. Finally, Chapter 9 highlights the main contributions of this project and suggests possible avenues for future research.

2. STATE-OF-THE-ART AUGMENTED REALITY SYSTEMS

2.1 Introduction

Rear-projection-based Virtual Reality (VR) devices, including the CAVE™ (Cruz-Neira et al., 1992) and the ImmersaDesk2™ (Czernuszenko et al., 1997), create a virtual environment projecting stereoscopic images on screens located between the users and the projectors (Figure 1). These displays suffer from image occlusion by the user's hand or any interaction device located between the user and the screen. When a virtual object is located at a reachable distance, the user can place his/her hand at a position that would be "behind" the virtual object. However, the hand will always look "in front" of the virtual object. This visual paradox confuses the brain and breaks down the stereoscopic illusion.

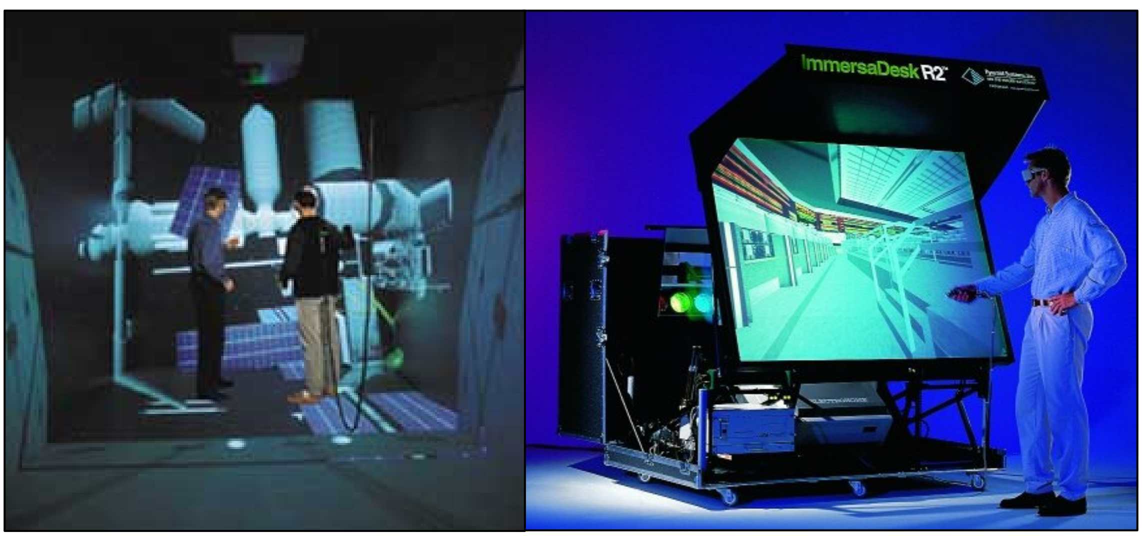


Figure 1. CAVE™ and ImmersaDesk2™. (Image courtesy of Fakespace)

Augmented Reality (AR) displays are more suitable for haptic applications than traditional VR devices because they allow the user to interact with virtual objects without occluding the stereo images. Most current AR systems use either a head mounted display (HMD) or a half-silvered mirror to create the virtual environment.

HMD-based AR systems render stereo images on a pair of transparent Liquid Crystal Displays (LCDs) allowing users wearing the HMD to see both real and virtual objects. Since they do not present occlusion problems, they might be suitable for haptics. However, like most VR systems, they suffer from another common problem known as “accommodation/convergence conflict” (Hiruma and Fukuda, 1993) (Mon-Williams and Pascal, 1995) (Okuyama, 1998). *Accommodation* is the muscle tension needed to change the focal length of the eyes’ lenses in order to focus at a particular depth. *Convergence* is the muscle tension to rotate both eyes so that they face the focal point. In the real world, when looking at distant objects the convergence angle between both eyes approaches zero and the accommodation is minimum (the cornea compression muscles are relaxed). When looking at close objects, the convergence angle increases and so does the accommodation. The brain determines the actual distance to an object on sight according to the constant relationship between convergence and accommodation.

In computer graphics, stereo visualization is achieved by defining a positive, negative, or zero parallax depending on the position of the virtual object with respect to the projection plane (or screen) of the stereoscopic display. Figure 2 shows how convergence and accommodation in the user’s eyes are affected by the position of the virtual objects in the virtual environment. When the user looks at computer-generated images on the stereoscopic display, the convergence angle between eyes still varies as the

3D object moves back and forward, but the accommodation always remains the same (the distance from the eyes to the screen is constant). When accommodation conflicts with convergence, the brain gets confused and may cause headaches and dizziness.

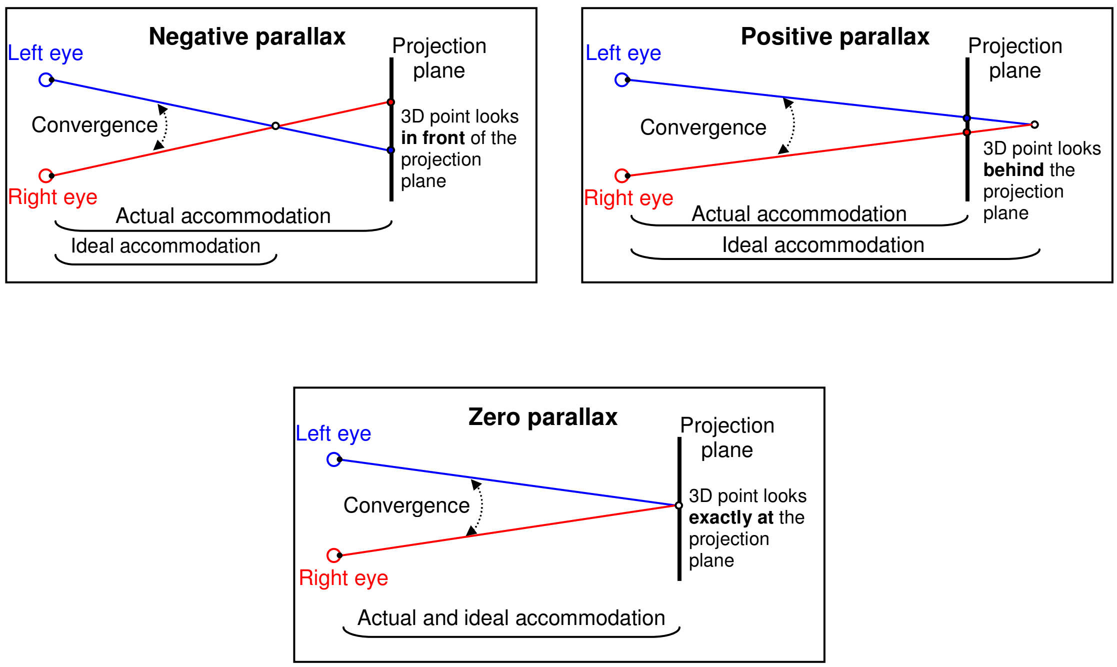


Figure 2. Accommodation/convergence conflict.

AR devices that use a half-silvered-mirror create a virtual projection plane formed by the reflection of the screen of a stereoscopic monitor. The user's hands, located behind the mirror, are integrated with the virtual space and provide a more natural means of interaction. The user can still see his/her hands without occluding the virtual objects.

When the virtual object is exactly located at the projection plane (zero parallax) the accommodation/converge conflict is eliminated. Since in most mirror-based AR systems the virtual objects are located close to the virtual projection plane, the conflict is minimized, resulting in a more realistic and pleasant experience than with traditional VR devices or even HMD-based AR systems.

2.2 Consideration for comparison of Augmented Reality systems

More realistic user interaction and better human perception make AR systems superior to VR systems. However, not every AR device is appropriate for surgical simulation. Issues such as pixel density, visual acuity, graphics/haptics relationships, etc. must be considered.

Pixel density is defined as the ratio between the display resolution and the size of the screen. It is measured in pixels per inch (ppi). The human vision can easily distinguish details up to 300 ppi.

Visual acuity is a measurement of a person's vision. Zwern (1995) computes the visual acuity of stereoscopic displays as a function of the field of view (FOV) and display resolution:

$$VisualAcuity = \frac{20}{FOV * 1200 / resolution}$$

Normal visual acuity is 20/20. In the US, 20/200 is the limit for legal blindness. This means that a legally blind individual would have to stand 20 feet from an object to see it with the same degree of clarity as a normally sighted person could from 200 feet. While 20/40 is considered the limit at which automobile drivers are permitted to drive without the need to wear corrective eyewear, 20/30 is the limit for emergency vehicle drivers.

The essential idea behind haptic AR systems is keeping both graphical and haptic representation of the virtual object perfectly synchronized to each other to simulate what occurs in the real world. To achieve realistic eye-hand coordination, the system must allow the user to see and touch exactly the same 3D spot of the virtual environment. This graphics/haptics collocation must be maintained at all times for a more believable experience.

Another important issue to consider is the possibility of reading text. Since the half-silvered mirror reflects the screen image, the reflected text is horizontally inverted and cannot be read. The ability of reading text is useful not only for real-time simulation, but also during software development. Programming and compiling on one workstation with a regular monitor and running the simulation on another one connected to the AR device makes software development very inconvenient, since going back and forth between two workstations would be needed.

The final aspect to be considered is the position of the screen with respect to the virtual projection plane. The half-silvered mirror can be considered as a bisector between the screen and the reflected image (located at the virtual projection plane). Due to the transparency of the half-silvered mirror, the brightness of the reflected image is approximately half of that of the original image on the screen. For that reason, the user should see only the reflected image but not the image directly coming from the real screen. Should the user’s FOV include both a brighter image from the screen and a dimmer image at the virtual projection plane, it would be very distracting.

Examples of previously existing haptic AR devices are:

- PARIS™ (Johnson et al., 2000)
- Reachin display (Stevenson et al. 1999)
- 3D-MIW (SenseGraphics)
- 3D-LIW (SenseGraphics)

We will analyze the features and drawbacks of each one of these systems based on display resolution, pixel density, visual acuity, graphics/haptics collocation, text readability, screen location, comfort, and cost.

2.3 PARIS™

PARIS™ (Personal Augmented Reality Immersive System) is a projection-based AR system created by the Electronic Visualization Laboratory at the University of Illinois at Chicago (UIC) (Johnson et al., 2000). It uses two mirrors to fold the optics and a translucent black rear-projection screen illuminated by a (Christie) Mirage 2000 stereo DLP (Digital Light Processing) projector (Figure 3). The user looks through a half-silvered mirror that reflects the image projected onto the horizontal screen located above the user's head. The reflected image creates a large virtual projection plane collocated with a (SensAble Technologies) PHANToM Desktop haptic device.

The stereoscopic effect is perceived by the user wearing a pair of shutter goggles, which are synchronized with the graphics card that renders left and right views alternatively. This wireless synchronization is done between an infrared emitter connected to the graphics card and a receiver on the goggles. This technique is called active or frame-sequential stereo.

2.3.1 <u>Advantages</u>

- Due to its large screen (58” x 47”), PARIS™ provides 120º of horizontal FOV and, therefore, it offers a high degree of immersion.
- Like the CAVE™ and ImmersaDesk™ devices, PARIS™ uses either an (Ascension Tecnhologies Corp.) pcBIRD or a Flock of Birds tracking system to track 3D positions and orientations of the user’s head and hand. The head tracking system enhances the graphics/haptics collocation because even when the user moves his or her head, a proper viewer-centered perspective is displayed on the virtual projection plane.
- PARIS™ screen is properly located outside the user’s FOV.

Figure 3. Personal Augmented Reality Immersive System (PARIS™).
(Image courtesy of the Electronic Visualization Laboratory)

2.3.2 Disadvantages

- The projector resolution used by PARIS™ is SXGA (1280 x 1024) @ 108 Hz, giving a pixel density of 22 ppi. Considering its horizontal resolution and FOV, its visual acuity is computed as follows:

$$\frac{20}{120^{\circ} * 1200 \big/ 1280\, pixels} = \frac{20}{112.5}$$

- The resulting visual acuity is worse than the required visual acuity needed to drive in the US and close to the limit of legal blindness. Therefore, PARIS™ is not appropriate for surgical simulation, which demands distinguishing small anatomical details in the virtual patient.

- Regarding text readability, PARIS™'s projector can horizontally flip the image, and therefore, the user can read text on the reflected image. However, its poor visual acuity makes reading very unpleasant and totally inappropriate for extended use during software development.
- The haptic workspace of the PHANToM Desktop™ is 6.4" W x 4.8" H x 4.8" D, which is just a small portion of the graphic workspace provided by the 75" screen diagonal (Figure 4). The mismatch in size between the graphic and haptic volumes causes that only a small area of the graphics volume can be touched with the haptic device, and just few pixels are used to display the collocated objects.
- Finally, due to the fact that an expensive stereo projector and complicated assembly operations are required, its cost is prohibitively high for large-scale deployment.

Figure 4. Relationship between graphic and haptic workspaces in PARIS™.
(Image courtesy of the Electronic Visualization Laboratory)

2.4 Reachin display

The Reachin display is a low-cost AR system, also known as the CSIRO Haptic Workbench (Stevenson et al. 1999). The device displays 3D images on a 17" CRT monitor with active stereo technique. A small translucent mirror reflects the monitor image and creates a small virtual projection plane collocated with a workspace of a SensAble PHANToM Desktop haptic device. A (3DConnexion) 6-DOF SpaceBall device is also provided to manipulate 3D objects in the virtual environment (Figure 5).

Figure 5. Reachin display.
(Image courtesy of SenseGraphics)

2.4.1 Advantages

- The Reachin monitor resolution is 1280x720 @ 120 Hz. Since the CRT screen is 17” diagonal, the pixel density is approximately 75 ppi, a significant improvement over PARIS™.
- With a horizontal FOV of 35º, the visual acuity of the Reachin display is higher, resulting in a better perception of small details:

$$\frac{20}{35^{o}*1200 \Big/ 1280\,pixels} = \frac{20}{32.81}$$

- Other advantage of the Reachin display is the fact that graphic and haptic workspaces match, so the user can touch all the virtual objects rendered in the virtual environment.
- Since inexpensive assembly and off-the-shelf components are used, its cost is low.

2.4.2 <u>Disadvantages</u>

- Since the image reflected on the mirror is horizontally inverted, the Reachin display cannot be used for software development. In fact, to overcome this drawback, a proprietary library (Reachin API) must be used to display properly inverted text on virtual buttons and menus along with the virtual scene.
- Another substantial problem of the Reachin display is the lack of head tracking. It assumes the user's head is at a fixed position at all times, so graphics/haptics collocation is only achieved at a particular sweet spot, and progressively degraded as the user moves his head while looking at the virtual scene from a different angle. Even incorporating head tracking to Reachin to improve graphics/haptics collocation would not work. The reason is described as follows.
- Because the Reachin display forces the user to keep his or her head at the sweet spot, the use of a small mirror is enough to reflect the monitor image. However, allowing the user to move out of the sweet spot would make the reflected image

to be chopped off by the mirror frame and, therefore, the augmented reality illusion would be completely broken.

- Unlike PARIS™, the monitor screen of the Reachin display is too close to the working volume. Thus, the brighter image coming from the monitor is in the user's FOV, becoming an important distracting factor.

2.5 SenseGraphics 3D-MIW

3D-MIW (Mobile Immersive Workspace) is a small and very portable AR system, which is ideal for quick on-the-road demonstrations. Commercialized by SenseGraphics, it consists of a (Sharp) Actius RD3D laptop and a SensAble Technologies PHANToM Omni haptic device (Figure 6).

2.5.1 Advantages

- The laptop has an auto-stereoscopic LCD display that renders 3D images without requiring the user to wear any stereo goggles.
- It is relatively inexpensive and very compact.
- Due to the position and orientation of the laptop screen and mirror, only the reflected image is visible. This fact helps to eliminate distractions.

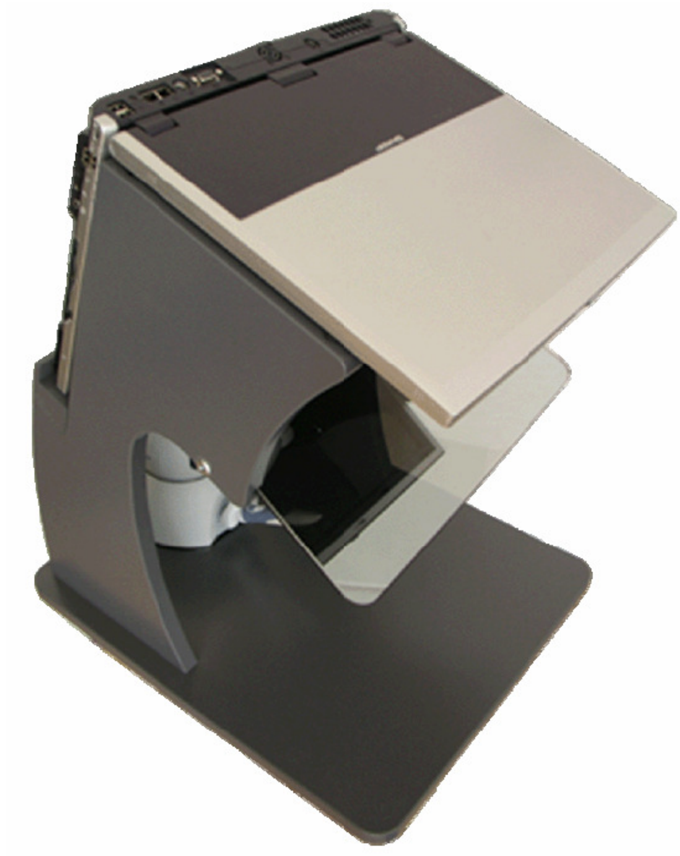


Figure 6. SenseGraphics 3D-MIW. (Image courtesy of SenseGraphics)

2.5.2 Disadvantages

- The resolution in 3D mode is 512x768 pixels per eye, with a pixel density of 60 ppi, which is insufficient for surgical simulation.
- Given a horizontal FOV of 35º, the visual acuity is also insufficient:

$$\frac{20}{35^{\circ}*1200 / 512\,pixels} = \frac{20}{82.03}$$

- The user has to keep the head static at a particular spot to perceive a correct stereo image. As the user moves his or her head, pseudo-stereo (where left and right views are reversed) or double images are perceived, breaking the 3D illusion completely.
- Like the Reachin display, the haptics/graphics collocation is also poor because of its lack of a head tracking system.
- Finally, the image is inverted, so the device is not suitable for application development either.

2.6 SenseGraphics 3D-LIW

3D-LIW (Large Immersive Workspace) is a new low-cost projection-based AR system also commercialized by SenseGraphics. It consists of an (InFocus™) DepthQ™ stereo DLP SVGA projector, with a screen size of 40” diagonal, and a large-area SensAble PHANToM Premium 3.0 haptic device. It also uses an active stereo technique (Figure 7).

2.6.1 Advantages

- Considered as an inexpensive alternative to PARIS™, its large working volume is ideal for large haptic devices.
- It uses a head tracking system, which can achieve better graphics/haptics collocation than other SenseGraphics products.

Figure 7. SenseGraphics 3D-LIW. (Image courtesy of SenseGraphics)

2.6.2 <u>Disadvantages</u>

- With a resolution of 800x600@120 Hz, and a FOV of approximately 60°, it offers a slightly better visual acuity than that of PARIS™, but still not enough for surgical simulation:

$$\frac{20}{60^{o}*1200\Big/800\,pixels} = \frac{20}{90}$$

- The PHANToM Premium 3.0 is appropriate for full-arm movement and the 3D-LIW graphic workspace perfectly matches its haptic workspace. However, the resolution of this haptic device is too low for the precise hand movements needed for surgical simulation. If the small PHANToM Desktop is used, then there would be a mismatch between graphic and haptic workspaces.
- Similar to Reachin display, the screen is in the user's FOV and, therefore, very distracting.
- Finally, its low visual acuity makes 3D-LIW not suitable for software application development.

2.7 Chapter conclusions

An ideal system for haptics-based surgical simulation should possess the following attributes:

- The system should allow the user's hands to be freely integrated with the virtual 3D space and provide a natural means of interaction. Ideally, movement or placement of the user's head or hand should not occlude or interrupt the stereoscopic display;
- The user should be able to see and touch any 3D point in the virtual environment at the same location in physical space to maintain realistic eye-hand coordination (graphics/haptics collocation). Essentially, the virtual experience should be as close to real as possible;

- Visual acuity of the display should be as close to perfect vision (20/20) as possible;
- The stereoscopic rendering of the 3D scene should self-adjust as the viewer's perspective changes. The user should be able to see virtual objects from different perspectives by simply moving his or her head, just like in the real world.
- Size of workspace should be sufficient large to allow substantial head movement and dual-hand interaction with the virtual 3D objects;
- The system should provide the ability to read any text on the display, even during the application development process;
- The screen should be outside of the user's FOV;
- Off-the-shelf devices should be used to minimize cost.

No Augmented Reality system currently on the market has all of these attributes. One of the goals of this project was to create the first system that is able to meet all these requirements. It should also serve as a common platform for both development and simulation of open surgical procedures such as ventriculostomy, combining the best features and overcoming the limitations of previously existing AR systems.

3. VENTRICULOSTOMY AND PREVIOUS SIMULATORS

3.1 Introduction

Ventriculostomy is an open neurosurgical procedure for measuring the intracranial pressure (ICP) as well as for providing therapeutic cerebrospinal fluid drainage to lower the ICP (Prabhu et al., 2004). After a small incision is made and a burr hole is drilled in a strategically chosen spot on the patient's skull, a ventriculostomy catheter is inserted aiming for the ventricles. A distinct puncturing sensation is felt as the catheter enters the frontal horn of the lateral ventricle. Using a pressure transducer system the excess spinal fluid is drained to reduce the ICP (Lang and Chestnut, 1994).

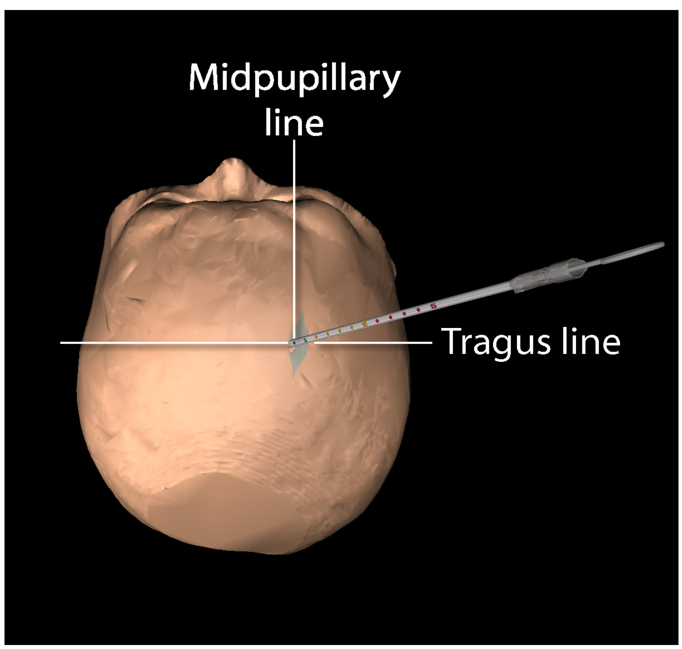


Figure 8. Burr hole located at Kocher's point.

3.2 How the ventriculostomy procedure is performed

A twist drill is used to make an opening in the skull over Kocher's point (at about 10 cm. from the eye along the midpupillary line) (Figure 8). The surgeon then places the tip of the catheter in the burr hole and orients the catheter based on certain anatomical landmarks: the medial canthus of the ipsilateral eye, in the axial plane (Figure 9), and the tragus of the ipsilateral ear, in the sagittal plane (Figure 10). The catheter, also known as extra-ventricular drain (EVD), is slowly inserted through the brain following a straight-line trajectory until a characteristic "pop" is felt as the lateral ventricle is cannulated. After the puncturing sensation is felt, the tip of the catheter is advanced few centimeters deeper to reach the opening of the foramen of Monro, located on the ipsilateral frontal horn of the lateral ventricle. The surgeon's goal is to hit the ventricle preferably in the first attempt but most definitely within the first three attempts. Otherwise, intraparenchymal pressure monitoring devices need to be placed because of potential injury to the cerebrum.

3.3 When it is performed and what risks are associated

Ventriculostomy is a high volume, low morbidity procedure that is commonly employed for treatment of head injury and stroke. Diagnostic information about ICP is available through the procedure. In addition, ventriculostomy may provide lifesaving therapeutic drainage in cases of symptomatic intracranial hypertension (hydrocephalus).

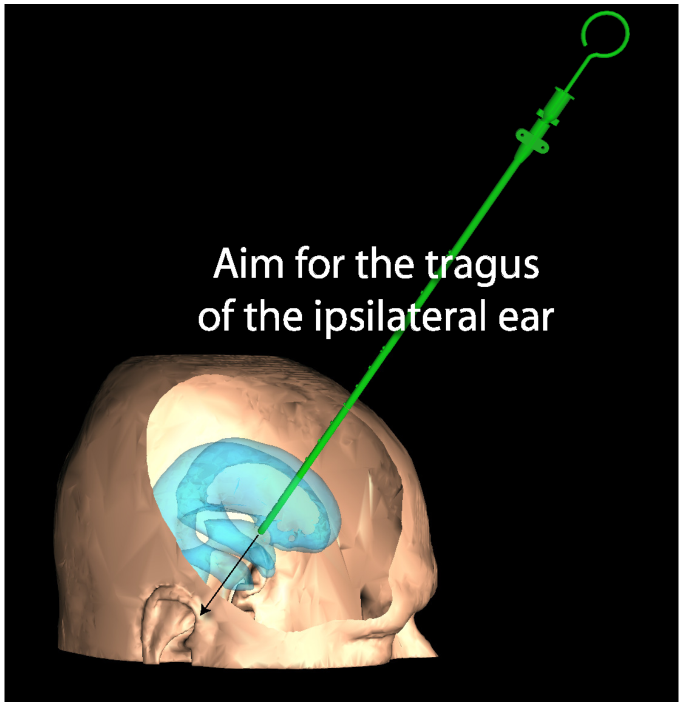


Figure 9. Landmark in the axial plane.

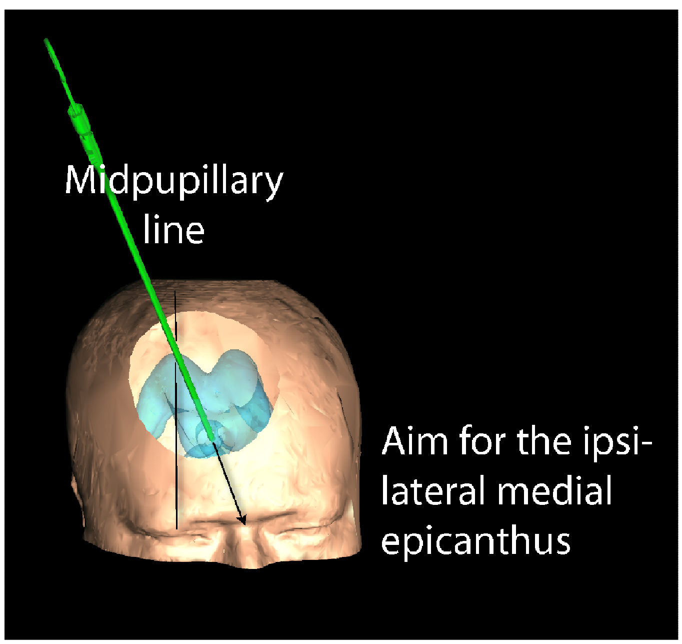


Figure 10. Landmark in the sagittal plane.

The most significant morbidities associated with ventriculostomy include hemorrhage, catheter misplacement, and infection (Paramore et al., 1994). Catheter misplacement can cause significant morbidity if eloquent structures are disrupted by passage of the catheter. Trajectory guides can improve catheter tip placement accuracy without altering ventricular cannulation rates (O'Leary et al., 2000). Neuronavigation with computer-assisted guidance has been shown to improve catheter positioning for shunt placement in the OR (Gil et al., 2002) but may not be practical in the Intensive Care Unit (ICU) or emergency department setting. Hemorrhage can be precipitated by violation of even small vessels. Multiple catheter passage attempts may also result in a higher risk of hemorrhage (Kanter et al., 1991). Just as importantly, failure to cannulate the ventricle with catheter malposition does not allow therapeutic cerebrospinal fluid drainage and may produce unreliable ICP data (Bullock et al., 1995). Optimal catheter trajectory and positioning are critical to prevent damage to vital neural and vascular structures. Clearly, the consequences are significant for proper technique education.

3.4 Why it needs to be simulated

Recently, Huyette et al. (2008) conducted a study to determine the accuracy of successful ventriculostomy procedures performed at the University of Missouri in Columbia. The study consisted of a retrospective evaluation of Computed Tomography (CT) scans of 97 patients who underwent free-hand coronal ventriculostomy catheter placements at that institution's ICU. The study revealed that typically 2 passes per successful placement were required, and when successful, the catheter tip was placed at 16.1 ± 9.6 mm (average ± standard deviation) from the ideal target (the foramen of

Monro). This is considered suboptimal. More surprisingly, it was found that only a mere 57% of the ventriculostomy procedures were successfully performed, and more than 22% of the catheter tips were placed outside of the ventricles, resulting in complete failures.

On top of that, ventriculostomy is one of the most frequently performed neurosurgical procedures (e.g., about 300 interventions per year at the University of Illinois Medical Center). While considered one of the most basic neurosurgical skills, the high volume and critical nature of the procedure necessitate proper technique and application. Thus, the sheer number increases the risk profile and the need for an effective training and simulation tool, and standardized evaluation of neurosurgeons.

3.5 Previous ventriculostomy simulators

Few ventriculostomy simulators have been developed in the last decade. Philips and Nigel (2000) and John and Phillips (2000) developed a cross-platform, web-based ventriculostomy simulator that allows virtual catheter positioning and trajectory determination relative to a 3D virtual head with a 2D mouse (Figure 11). This form of visually reinforced learning for ventriculostomy training has also been described using operative Neuronavigational platforms (Krombach et al., 2000).

An auditory cue, in lieu of tactile feedback, signals ventricular cannulation. Since the 3D catheter manipulation with a 2D mouse is cumbersome and rudimentary, the effectiveness of these simulators is limited to improving the understanding of anatomical relationships relative to catheter position and trajectory. Due to the lack of force feedback they cannot reproduce the characteristic “pop” felt as the catheter penetrates the ventricles.

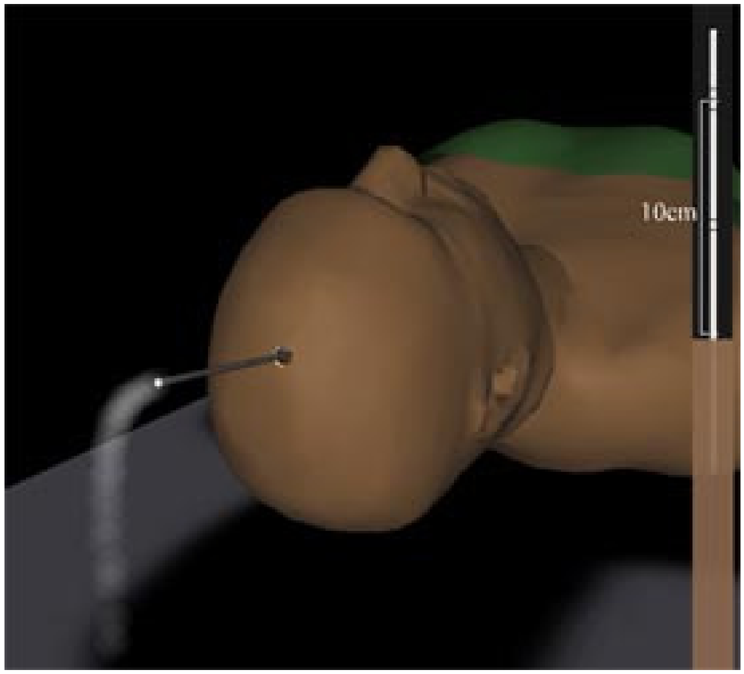


Figure 11. Web-based early ventriculostomy simulator.
(Image courtesy of Philips and Nigel, 2000)

To overcome this limitation, the first generation of haptic ventriculostomy simulators incorporated a haptic device to provide tactile feedback during virtual ventricular cannulation (Larsen et al., 2001) (Cros et al., 2002). The user manipulates the virtual catheter with the haptic device stylus in an AR environment implemented for the Reachin display (Figure 12). While the development of these first generation simulators created considerable excitement as novelty devices for ventricular cannulation, their usefulness for teaching and measuring neurosurgical expertise was still very limited for multiple reasons. First of all, during an actual ventriculostomy, the patient's head is placed supine and slightly raised. After calvarial trephination, the surgeon orients the catheter and defines a trajectory based upon superficial landmarks on the patient's head. The surgeon must move his/her head from one side of the patient's head to the other to locate the landmarks in the axial and sagittal planes. Head tracking is critical to simulate a dynamic viewer-centered perspective. Previous simulators have provided only static perspective and, thus, they fall short of simulating the psychomotor skill-set involved in determining catheter trajectory.

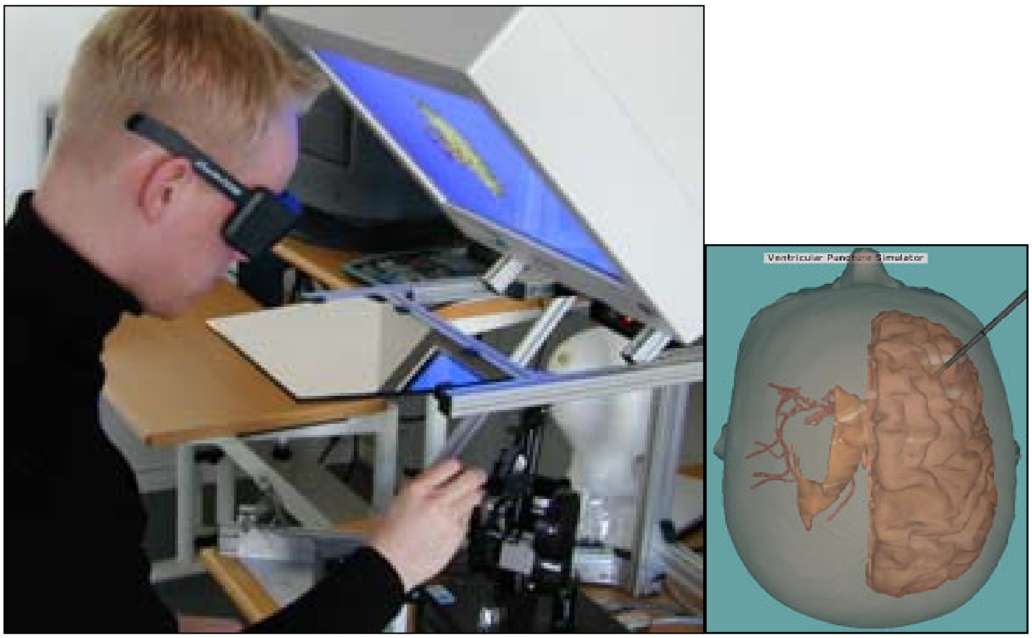


Figure 12. First-generation haptic ventriculostomy simulators.
(Image courtesy of Larsen et al., 2001)

Another important requirement of any realistic ventriculostomy simulator is perfect overlapping of the virtual catheter 3D image with the haptic stylus so that the user feels as though he/she is holding the catheter. The graphics/haptics collocation should be maintained all the time as the user moves his/her head. Previous attempts at ventriculostomy simulation were not able to address this issue, and the attention of the surgeon was diverted from the simulated procedure toward overcoming the visual dissociation of real and virtual objects. In effect, the simulators did not adequately reproduce a real ventriculostomy procedure.

A more recent attempt at ventriculostomy simulation has been developed by (Panchaphongsaphak et.al., 2006). This simulator utilizes a 1-DOF haptic device to simulate the advancement of a catheter into a plastic brain model mounted on a 6-DOF force-torque sensor (Figure 13). The base sensor detects position, orientation, and amount of force applied by the user. The non-collocated graphics rendering allows virtual trajectory visualization. Because the platform uses a physical 3D model of the brain, there is no need for graphics/haptics collocation to simulate catheter insertion. However, the authors found unrealistic haptic feedback deviated from the desired forces up to 20%, and tracking errors up to 5 mm when the user pushes the device against the brain model. Moreover, the lack of surgical landmarks on the plastic brain does not allow development of psychomotor skills needed to perform a real ventriculostomy.

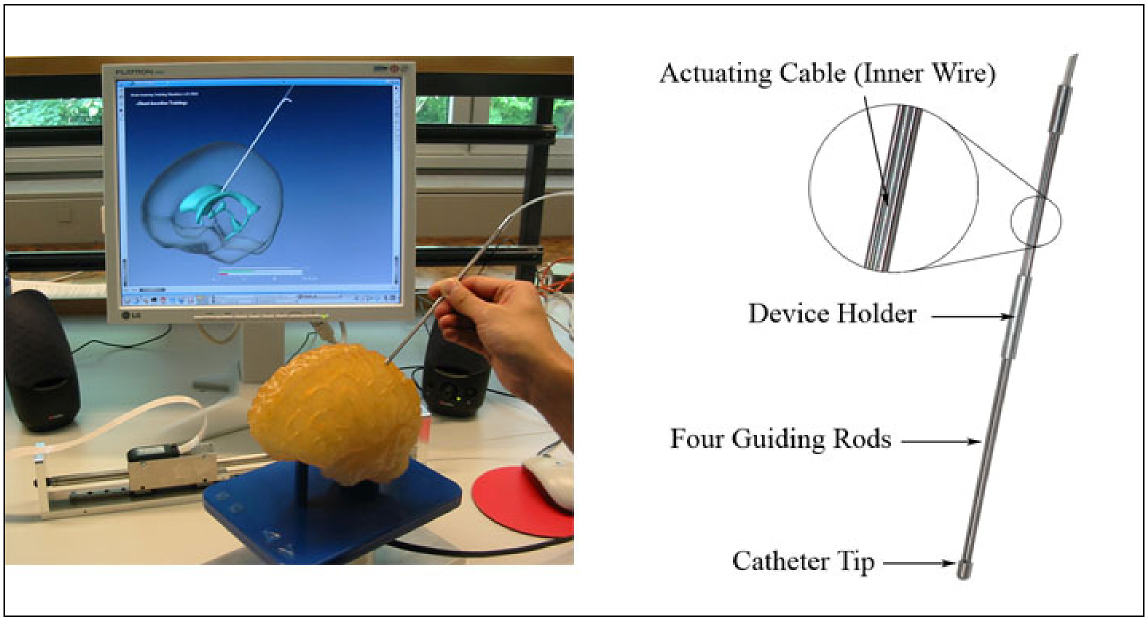


Figure 13. BRAINTRAIN ventriculostomy simulator.
(Image courtesy of Panchaphongsaphak et.al., 2006)

3.6 Chapter conclusions

In order to effectively simulate a real ventriculostomy procedure, the VR system should satisfy the following requirements:

- Haptic feedback to reproduce changes in the viscosity as the catheter passes through the brain parenchyma and into the ventricle, simulating the “popping” sensation that indicates successful catheter placement;
- Realistic 3D rendering of medical models extracted from real patients to simulate a spectrum of different scenarios between normal and extreme cases;
- Head tracking to render a dynamic viewing perspective by simply tilting or moving the viewer’s head while identifying the landmarks that guide catheter trajectory;

- Perfect graphics/haptics collocation to superimpose the virtual catheter with the haptic stylus all the time, even when the user moves the head changing his/her perspective;
- High display resolution and visual acuity to visualize fine anatomic details of the virtual patient's head and markings on the catheter;
- Ergonomic design to provide a comfortable posture simulating real working conditions in the ICU or in the OR;
- High quality stereoscopic visualization with low flickering to avoid eye strain even during long practices;
- Intuitive 3D manipulation with both hands in the working volume not only to provide haptic feedback but also to interactively define cutting planes to verify or rectify catheter placement facilitating the learning process.

None of the previously existing ventriculostomy simulators can meet all these requirements. They are unable to effectively simulate a real ventriculostomy procedure, and cannot help trainees to develop both tactile and psychomotor skills. Unrealistic catheter manipulation, poor graphics/haptics collocation and low visual acuity are some of the most important problems of previous simulators.

The following Chapters will focus on the design and implementation of the first high-fidelity haptics-based AR simulation system that allows Neurosurgery residents to develop both the tactile and psychomotor skills involved in a ventriculostomy procedure, overcoming major limitations of existing AR displays (discussed in the previous Chapter) as well as the limitations of previous ventriculostomy simulators.

4. HARDWARE DESIGN OF THE *IMMERSIVETOUCH* ®

4.1 Introduction

The drawbacks of previously existing simulation systems and their inability to effectively simulate open surgical procedures, such as ventriculostomy, motivated the design of a new Augmented Reality system. The *ImmersiveTouch*® is the first system that integrates a haptic device, with a head and hand tracking system, and a high-resolution and high-pixel-density stereoscopic display. Its ergonomic design provides a comfortable working volume in the space of a standard desktop. The haptic device is collocated with the 3D graphics, giving the user a more realistic and natural means to manipulate and modify 3D data in real time (Luciano et al., 2005).

This Chapter focuses on the challenges that were overcome to design the hardware of this next-generation AR technology, including positioning of the haptic device and virtual projection plane, relationship between the monitor and the half-silvered mirror, and use of a head and hand tracking system to track user's movements.

4.2 Positioning of haptic device and virtual projection plane

The first step in the design of haptic AR systems is to determine the haptic device position with respect to the user. We use a SensAble PHANToM Desktop haptic device. Ergonomic analyses were performed to identify the ideal position of the haptic device considering its working volume and a comfortable user's posture, including elbow and wrist support. Figure 14 shows the desired position of the haptic device.

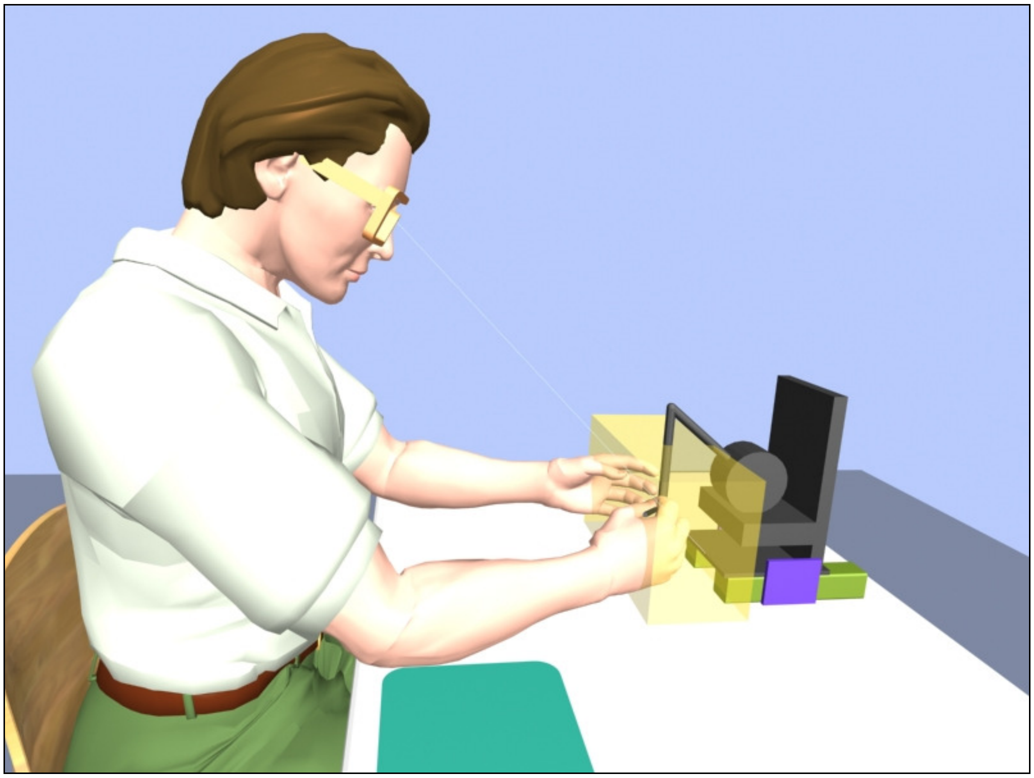


Figure 14. The haptic workspace.

Having the user looking straight at the haptic stylus (held at the origin of the haptic device coordinate system), an imaginary sight line from the user's glabella to the center of the haptic workspace is defined. The virtual projection plane is to be located exactly at the center of the haptic workspace and oriented perpendicular to that line. The final position and orientation of the virtual projection plane are considered the fundamental design constraints that define the remaining components of the AR system. The resulting angle of the virtual projection plane resulted to be 45° with respect to the table. (Figure 15).

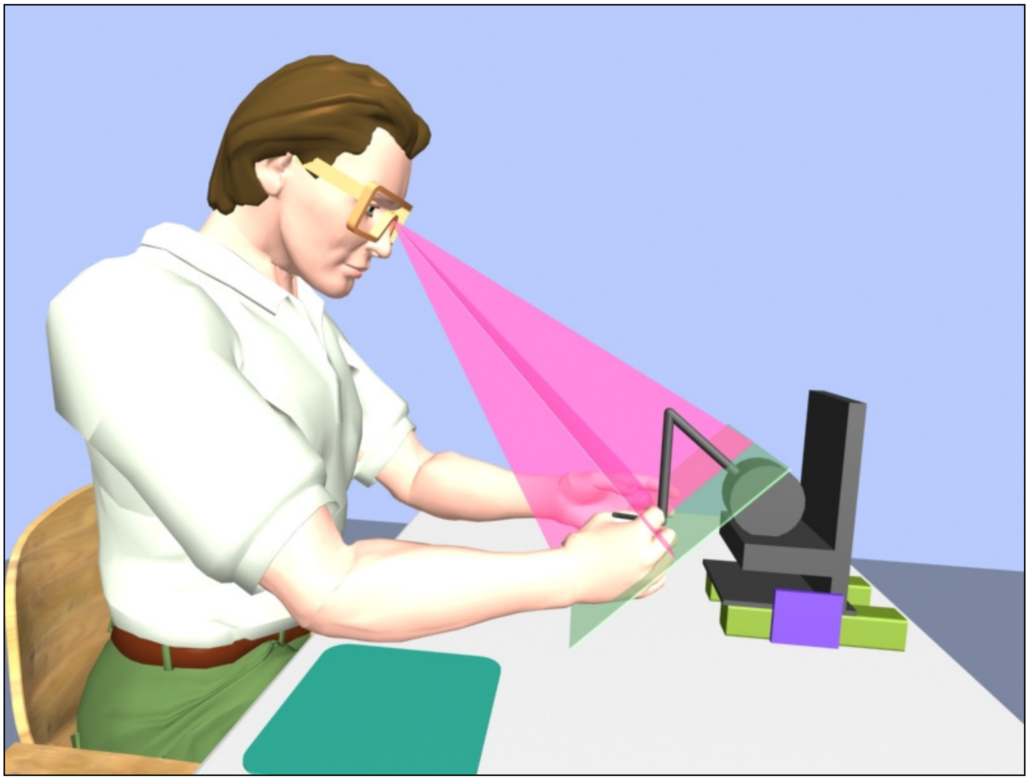


Figure 15. The virtual projection plane.

4.3 High-resolution monitor and half-silvered mirror

Knowing the desired position and orientation of the virtual projection plane, the following step is to study all possible layouts for the monitor and the mirror to maintain that fundamental constraint. The mirror corresponds to the bisector of the angle between the monitor screen and the virtual projection plane. Thus, both the mirror and monitor need to be coordinated in order to maintain the virtual projection plane at 45°, leading to multiple alternatives.

Multiple feasible layouts for the monitor and mirror that are able to keep the virtual projection plane as desired were modeled and analyzed with parametric Computer-Aided Design (CAD) software.

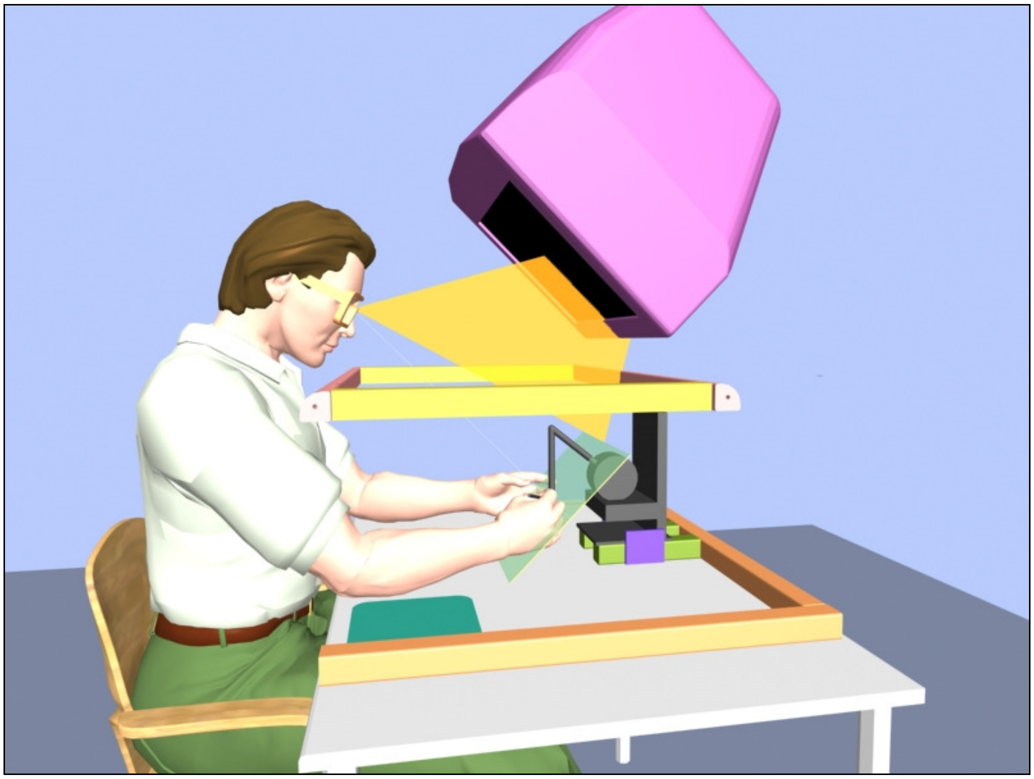


Figure 16. What if the mirror is horizontal?

Positioning the mirror horizontally, as in the Reachin display, moves the monitor inside the user's FOV when the user looks at the top of the virtual projection plane as illustrated in Figure 16. On the other hand, locating the monitor screen horizontally, as in PARIS™, the user's head occludes the monitor image reflected on the mirror (Figure 17). After analyzing both PARIS™ and Reachin display, the optimal layout in which the monitor is both outside the user's FOV and sufficiently separated from the user's head has been found, as shown in Figure 18.

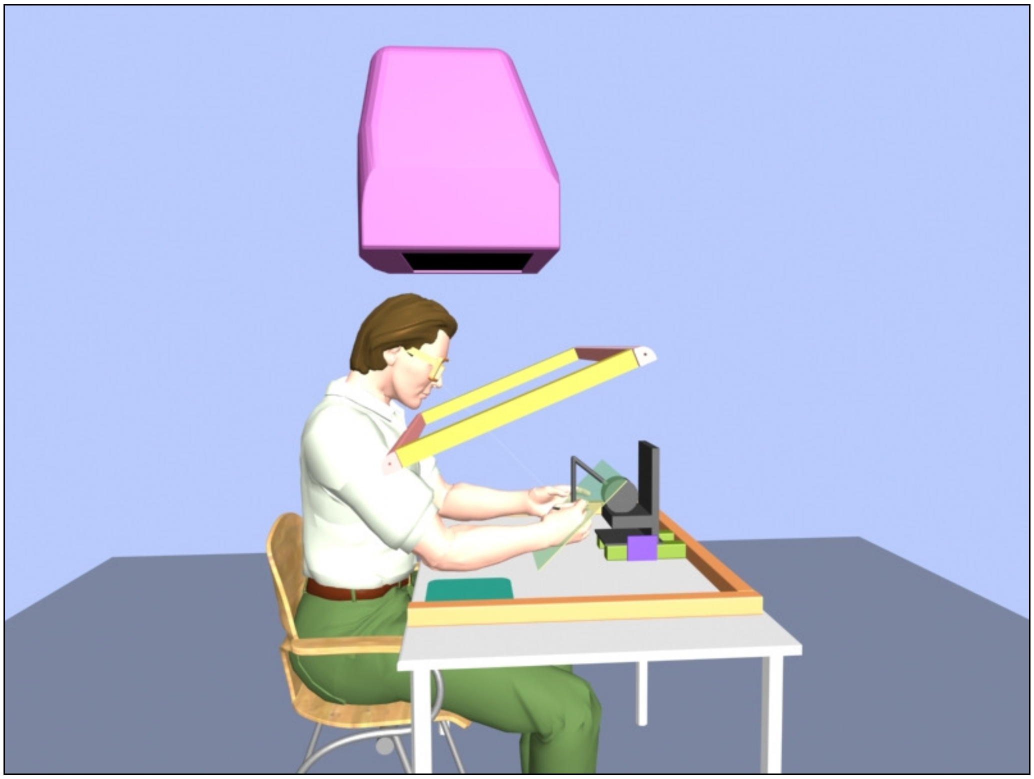


Figure 17. What if the screen is horizontal?

In order to obtain an acceptable pixel density for surgical simulation, a 22" monitor with a maximum resolution of 1600x1200 @ 100 Hz was considered. Since the monitor screen is 16" x 12", the pixel density is 100 ppi, which is even higher than that of the Reachin display. Given the position of the virtual projection plane with respect to the user, the horizontal FOV of the system is 33º. Therefore, the visual acuity resulted to be substantially close to ideal:

$$\frac{20}{33^{o}*1200/1600\,pixels}=\frac{20}{24.75}$$

Even though previous systems are able to provide 120 Hz of vertical refresh rate, experience has proven that 100 Hz is high enough to diminish the annoying flickering caused by the active stereo goggles, minimizing strain on the eyes.

As discussed in Chapter 2, the user must be able to read the text shown by the image reflected on the mirror. In the case of PARIS™, the projector itself does the image inversion. Unfortunately, regular CRT monitors do not provide that option. There are some hardware video converters that are connected between the graphic card and the monitor to mirror the image, but they are very expensive and do not support a resolution of 1600x1200@100 Hz. Therefore, it was decided to modify the electronics of the CRT monitor. Replicating an old trick in the consoles of arcade games in the ’80s, the wires of the horizontal deflector yoke of the monitor were reversed to flip the image. That resulted to be a very simple, but effective, solution.

4.4 Head and hand tracking system

Use of a head tracking system is fundamental to obtain a correct graphics/haptics collocation. In addition, head tracking allows us to render a correct viewer-centered perspective, in which both left and right views are perfectly aligned with the user’s eyes, even when the user tilts his/her head, maintaining a perfect stereoscopic visualization.

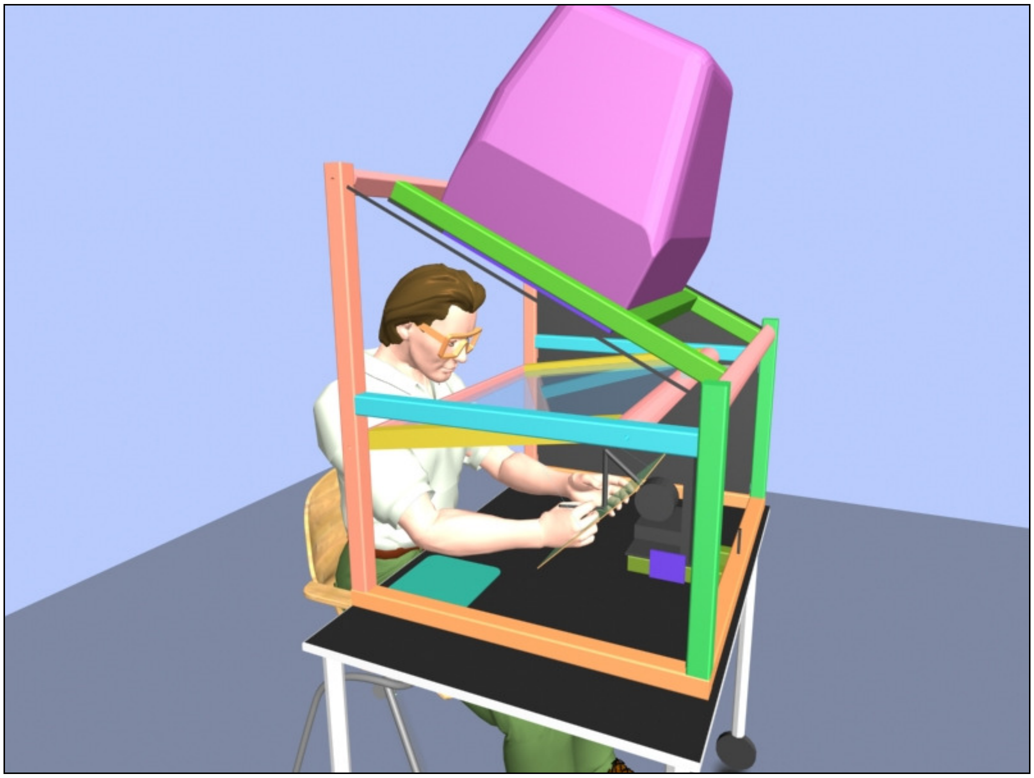


Figure 18. Final layout of mirror and monitor.

It is worth mentioning that the mirror is sufficiently wide (29”x21”) to allow the user to view virtual objects from different perspectives moving his/her head to the left and right (up to one foot) without breaking the visual illusion, overcoming the limitations of Reachin display and most SenseGraphics systems (Figure 19).

A 6 DOF electromagnetic tracker system is used to track both head and hand. The *ImmersiveTouch*™ is compatible with multiple trackers by Ascension Technologies, Corp., which offer high resolution, high accuracy and an occlusion-free solution. The electromagnetic tracker consists of a transmitter that generates a magnetic field and a set of receivers that detect the magnetic field and measure their 3D positions and orientations relative to the transmitter. A receiver is mounted on the stereo goggles to track the user's head. Another receiver is manipulated by the user to track his/her hand.

Hand tracking is very useful because it allows users to use both hands to interact with the virtual scene. While they can feel tactile sensations with the hand holding the haptic stylus, they can also use the tracked hand to move the 3D objects, manipulate lights, or define clipping planes in the same 3D working volume. For hand tracking, we use the SpaceGrips® (LaserAid) that holds an electromagnetic receiver and provides access to 4 buttons through a serial port.

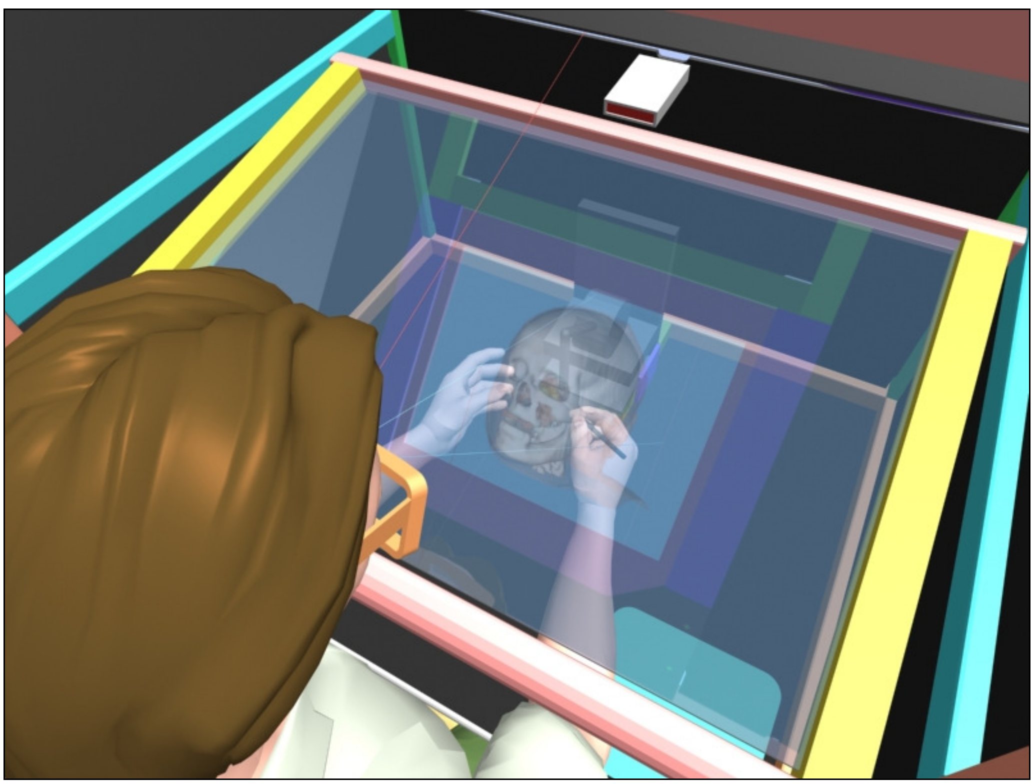


Figure 19. Wide mirror to allow proper viewer-centered perspective.

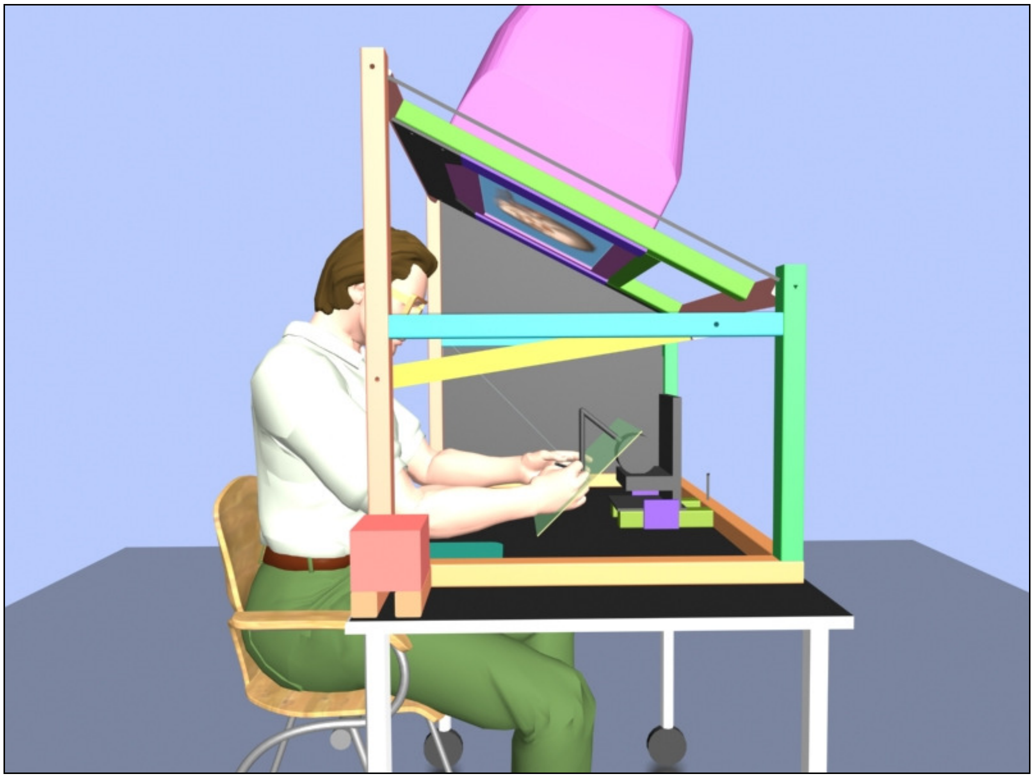


Figure 20. Optimal location of the tracker transmitter.

Deciding the location of the transmitter in the proximities of a CRT monitor is very challenging because of electromagnetic interferences between both devices. If the transmitter is located too close to the monitor, it incorporates magnetic noise to the monitor circuitry, making it unable to display a steady image. On the other hand, if the transmitter is located far away from the receivers, the accuracy of the tracking system decreases and severe jittering is produced that cannot be solved with any kind of filtering algorithm. By empirical noise analyses, it was found that the optimal location of the transmitter that is able to achieve satisfactory tracking range for the hand and head, while maintaining adequate distance from the monitor, is at the side of the device as shown in Figure 20.

Figure 21 shows the seamlessly integrated components of the *ImmersiveTouch*® system:

- A PHANToM Desktop haptic device (SensAble Technologies);
- A 6-DOF electromagnetic head tracking system (Ascension Technology Corporation);
- An active stereoscopic display provided by a high-resolution CRT monitor with CrystalEyes shutter glasses and infrared emitter (Real-D);
- A 6-DOF SpaceGrip hand manipulator with electromagnetic hand tracking system (LaserAid).

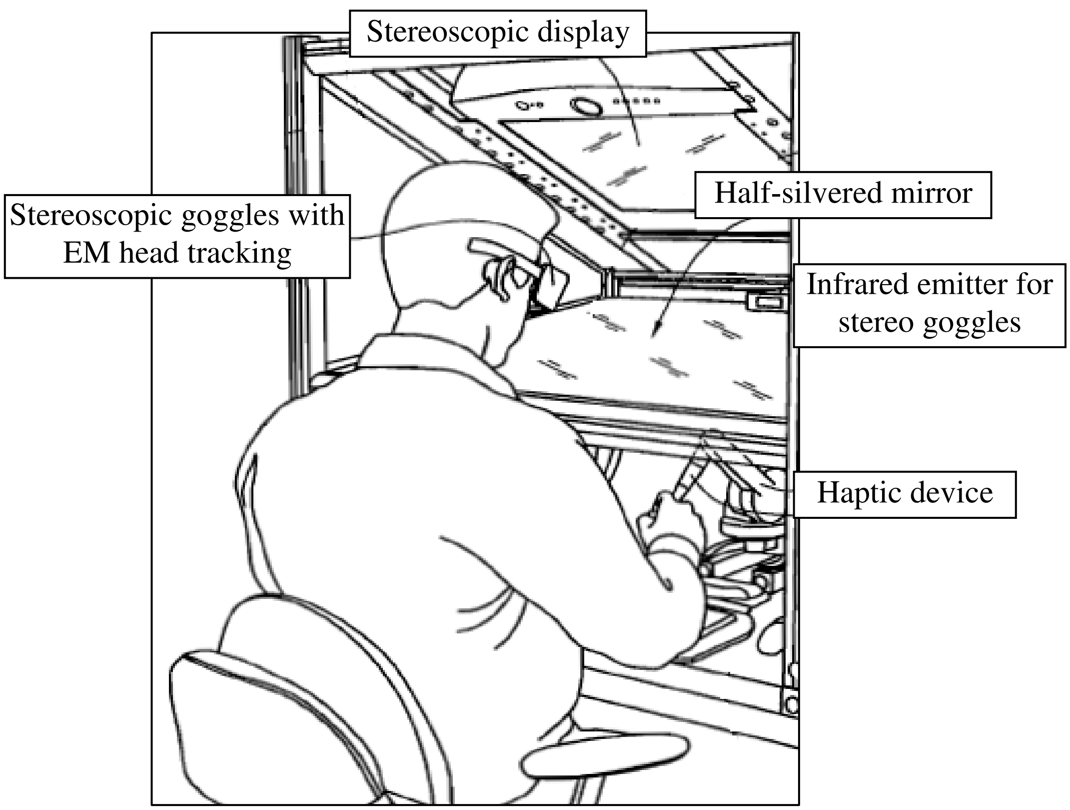


Figure 21. Components of the *ImmersiveTouch*®.

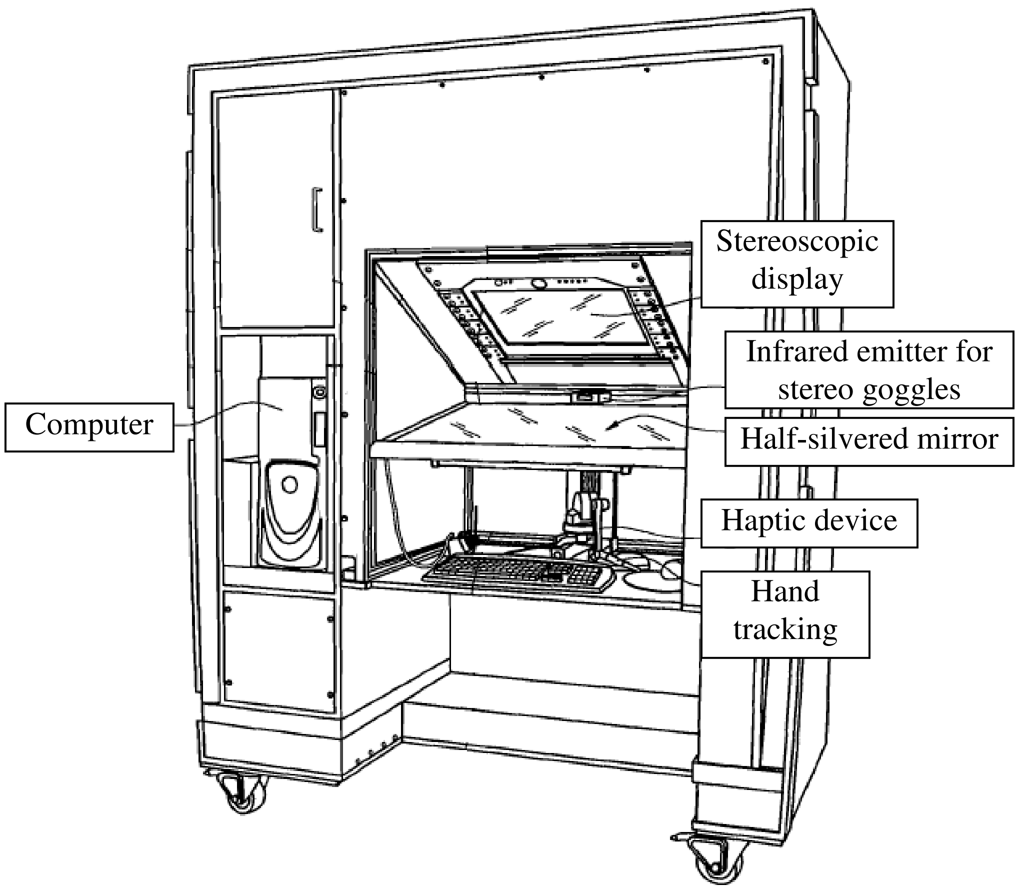


Figure 22. Final design of the *ImmersiveTouch*®.

Figure 22 shows the final design of the *ImmersiveTouch*® as a compact, self-contained unit for easy transportation and deployment.

4.5 Chapter conclusions

A novel Augmented Reality simulation system that is able to overcome the technologic limitations of previous devices has been designed and built. Compared to previous alternative systems, the *ImmersiveTouch*® system presents significant advantages, including more accurate graphics/haptics collocation, higher display resolution, higher pixel density, better visual acuity, and more comfortable workspace, making it unique for surgical simulation (Table I).

TABLE I

FEATURE COMPARISON WITH PREVIOUS SYSTEMS

Feature	PARIS™	Reachin display	3D-MIW	3D-LIW	*Immersive Touch®*
3D display resolution (pixels)	1280x1024	1280x720	512x768	800x600	1600x1200
Vertical refresh rate (Hz)	108	120	60	120	100
Pixel density (ppi)	22	75	58	25	100
Screen size (inches)	58x47	13x11	12x9	32x24	16x12
Visual acuity	20/112.5	20/32.81	20/82.03	20/90	20/24.75
Matching haptic and graphic volumes	-	√	√	-	√
Viewer-centered perspective	√	-	-	√	√
Comfortable workspace	√	-	-	√	√
Screen is outside user's FOV	√	-	√	-	√
Suitable for surgery simulation	-	-	-	-	√

5. *IMMERSIVETOUCH* ® VENTRICULOSTOMY SIMULATOR

5.1 <u>Introduction</u>

As discussed in Chapter 3, early ventriculostomy simulators provide some basic audio/visual feedback to simulate the procedure, displaying a 3D virtual model of a human head. Without any tactile feedback, the usefulness of such simulators is very limited. The first generation haptic ventriculostomy simulators incorporated a haptic device to generate a virtual resistance and "give" upon ventricular entry. While this advancement created considerable excitement as a novelty device for cannulating ventricles, its usefulness for teaching and measuring neurosurgical expertise was still very limited. Poor collocation between the haptic stylus as held by the surgeon and the visual representation of the virtual catheter, as well as the lack of a correct viewer-centered perspective, created confusion for the neurosurgeons, who diverted their attention from the actual ventriculostomy procedure to overcoming the limitations of the simulator.

The graphics/haptics collocation achieved by the *ImmersiveTouch*® is critical to the realistic recreation of the surgical experience. The translucent mirror used to create an Augmented Reality environment integrates the surgeon hands, the virtual catheter and the virtual patient's head in a common working volume. The surgeon can see his or her own hand holding a virtual catheter in the same location and space as he or she would for the actual procedure. In the *ImmersiveTouch*®, the user can interact with the virtual objects using both hands, holding the haptic stylus with one hand while defining arbitrary 3D cutting planes with the other hand.

This Chapter describes how the second-generation haptic ventriculostomy simulator succeeds over the major first-generation limitations by introducing a head and hand tracking system as well as a high-resolution high-visual-acuity stereoscopic display to enhance the perception and realism of the virtual ventriculostomy (Lemole et al., 2007).

Figure 23. Surgeon interacting with the *ImmersiveTouch*®.

5.2 <u>Initial setup</u>

A trainee sits at the working table of the *ImmersiveTouch*® simulator as shown in Figure 23. Electromagnetically tracked goggles are worn to stereoscopically view the reflected virtual reality image on the partially-mirrored viewing surface. A shift in the surgeon's head causes a corresponding change in perspective around the virtual patient head. These changes also collocate with the surgeon's hands as viewed through the trans-reflective mirror. A virtual catheter and other virtual working tools (light source and cut-away instruments) are also displayed in the collocated 3D space.

5.3 Preparation of the virtual patient for the procedure

The trainee is presented with a virtual patient head, viewed from an antero-rostral perspective, similar to patient positioning for ventriculostomy placement in the OR or ICU. The head is supine and raised about 30 degrees, but minor adjustments are permitted to the user.

A "Part-task" modular paradigm is used for the simulation. This assumes that only critical components of the procedure are modeled and simulated. As such, hair clipping, prepping and draping, skin incision, and calvarial trephination are presumed prior to the procedure. One or multiple pre-existing scalp incisions and burr holes are provided on the virtual head. The trainee must identify the most appropriate burr hole to choose according to the patient's anatomy and multiple CT scan images provided along with the 3D model of the virtual head.

5.4 Identification of superficial landmarks on the virtual patient

By grasping the haptic stylus with the dominant hand, the user is able to see a virtual catheter with appropriate measurement demarcations. A 3D model of a ventriculostomy catheter is collocated with the haptic stylus so the user perceives as he/she was actually holding a real catheter (Figure 24).

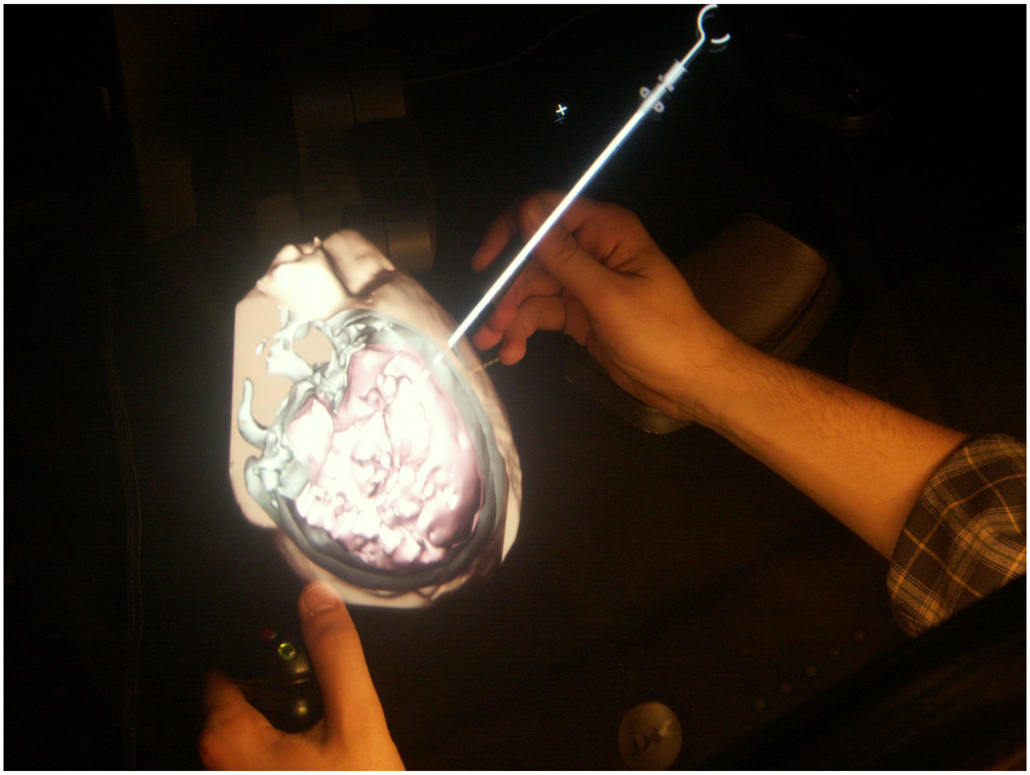


Figure 24. Collocation between the virtual catheter and haptic stylus.

The catheter tip is positioned over the burr hole while the optimal trajectory is determined. Superficial landmarks such as the ipsilateral medial canthus and tragus are easily visualized by changing the user's perspective (i.e. looking around the head) just as with the actual procedure, taking advantage of the head tracking capabilities of the *ImmersiveTouch*®. The perfect graphics/haptics collocation achieved by the simulator is maintained at all times, even when the user moves his/her head to identify the landmarks on the virtual patient's head.

Multiple ventriculostomy cases with different complexities are simulated: patients with normal anatomy and overt hydrocephalus (over-dimensioned ventricles), as well as with slit (compressed) and shifted ventricles in response to masses (tumors, hematomas).

Naturally, the surgeon has to account for these factors and modify the initial trajectory appropriately.

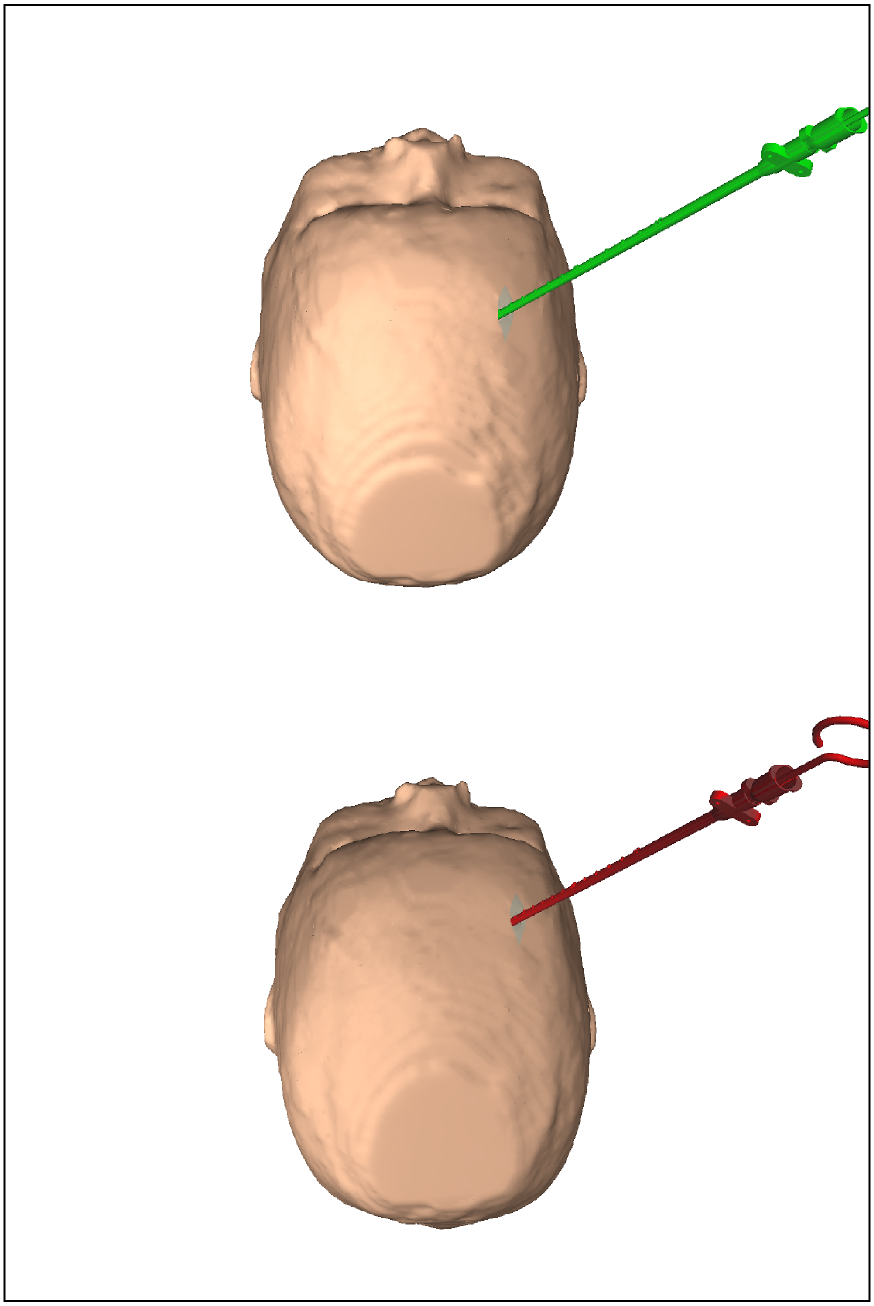


Figure 25. Green catheter indicates successful cannulation, while red indicates failure.

5.5 Insertion of the virtual catheter

As the catheter is advanced past the calvarium and enters the modeled 3D brain, the user feels a distinct increase in resistance simulating the viscosity of the brain parenchyma. When the catheter reaches the appropriate volumetric depth, there is a sudden release in haptic resistance corresponding to the "pop" often experienced when the ventricle is cannulated by piercing the pia or ependyma.

The haptic characteristics of the virtual patient's head were modified based upon feedback from neurosurgical faculty and senior residents. The final product was universally agreed to realistically simulate the tactile and visual components of the actual procedure.

A ruler on the ventricular catheter is also used to gauge the expected depth to ventricular cannulation. High resolution 3D images are crucial to be able to see the markings on the virtual catheter and the anatomical landmarks on the patient's head to define the catheter orientation and depth.

5.6 Performance evaluation

When the user believes the ventricular catheter is successfully placed, the 3D manipulator held in the other hand is used to freeze the virtual catheter in position. If the virtual catheter is in the virtual ventricular system it turns green, otherwise its color turns red (Figure 25).

The trainee can then use the cutting tool (indicated by the virtual scissors) to interactively define the 3D position and orientation of a clipping plane to see the interior of the virtual patient's head (Figure 26) and verify the catheter insertion to correlate experience with technique (Figure 27).

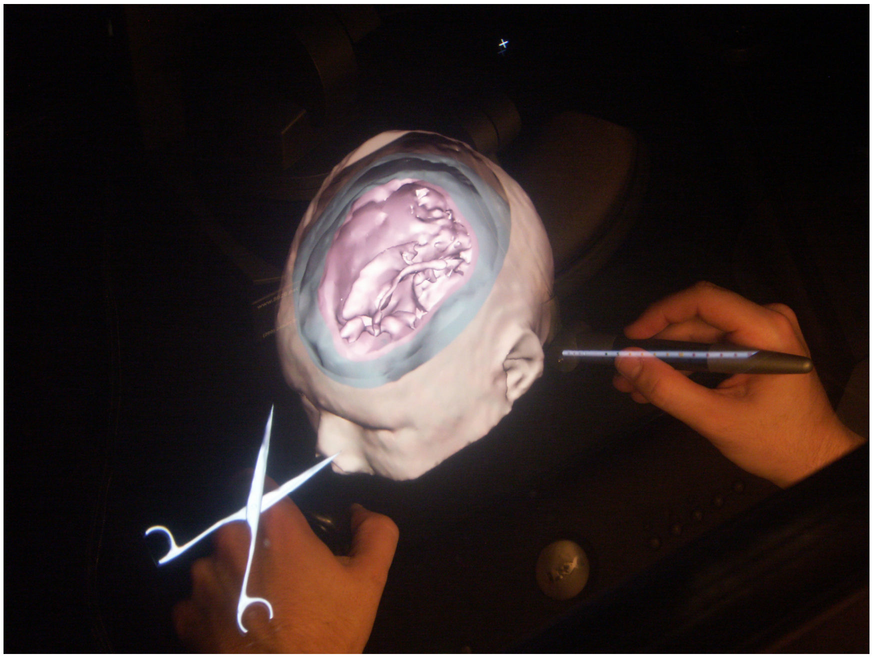


Figure 26. Interactive cutting tool.

The trainee's performance is measured as the Euclidean distance between the tip of the virtual catheter and a specified target (e.g. the foramen of Monro) for each trial, and stored for later statistical analyses.

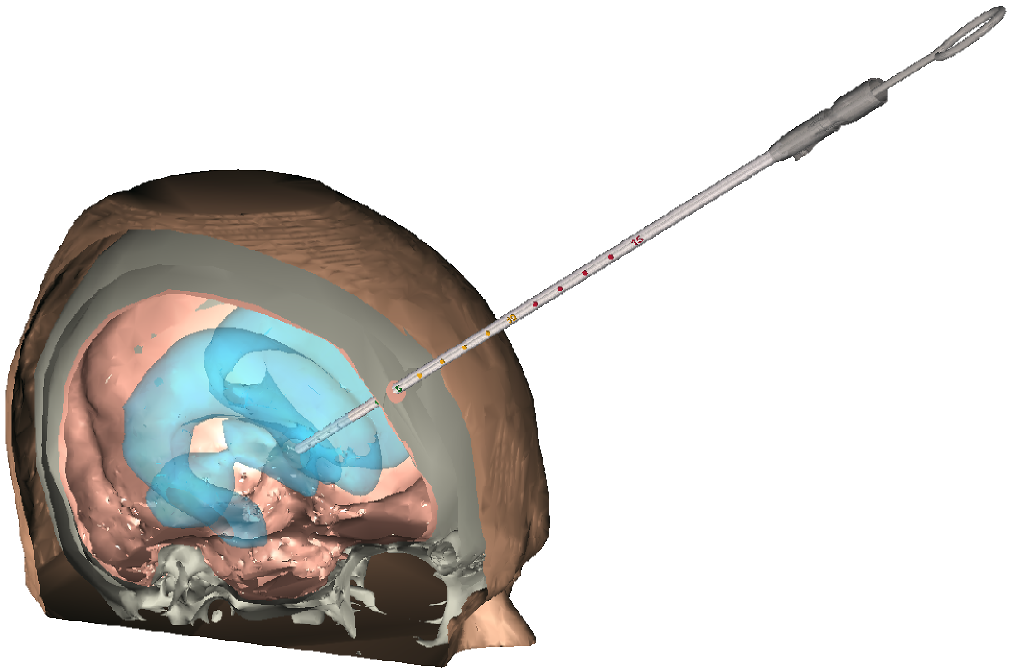


Figure 27. 3D visualization of the cannulated ventricles.

5.7 Chapter conclusions

By taking advantage of the seamless integration of the haptic device, the high-resolution stereoscopic display, and the head and hand tracking system, the *ImmersiveTouch*® facilitated the development of a realistic haptics-based open neurosurgical simulator that accurately reproduces the part-task experience of cannulating the ventricles with a virtual ventricular catheter.

The ventriculostomy simulator allows the neurosurgeon to replicate most of the crucial steps followed in the ICU during a real ventriculostomy procedure. The trainee can position the patient in a similar way to a real OR. Then he or she can determine the ideal burr hole, choosing among multiple pre-drilled burr holes. By simply moving his/her head around the virtual patient's head, the surgeon can identify the superficial landmarks in the axial and sagittal plane, and insert the catheter while feeling both the resistance of brain tissue and the ependymal "pop" as the ventricle is cannulated.

In addition, immediate performance evaluation is presented to the trainee, who can cut through the virtual 3D head to visualize the shape and location of the internal ventricular structure and the final position of the catheter tip to determine whether the surgical procedure has been successful or not. Furthermore, accuracy of the catheter insertion is measured and automatically stored by the simulator. The ventriculostomy simulator has demonstrated to be highly intuitive and experience has shown that just a few minutes are needed for the trainee to become familiar with the simulation system.

6. SOFTWARE DESIGN OF THE VENTRICULOSTOMY SIMULATOR

6.1 Introduction

The ventriculostomy simulator seamlessly integrates the 3D stereo display with the head and hand tracking system and the haptic device provided by the *ImmersiveTouch*® system to simulate the surgical procedure (Figure 28). This Chapter focuses on the software design as well as some implementation details of the major processing modules of the simulator (Luciano et al., 2006). Data flow diagrams show the interrelationships between the hardware and software components (Figure 29).

In a pre-processing phase, the MRI and/or CT scanners provide multiple 2D slices of the real patient's head to create a 3D model of the virtual patient. During real-time simulation, the haptic device tracks the 3D position and orientation of the virtual catheter. As the user inserts the virtual catheter inside the virtual head, force feedback is sent to the haptic device to be felt by the user. Haptic materials are fine-tuned by the experienced neurosurgeon to obtain realistic force feedback results. The electromagnetic receiver in the SpaceGrips gives 3D position and orientation of the user's hand to define cutting planes and to explore the virtual patient's anatomy. Finally, the head receiver mounted on the stereo goggles gives the 3D position and orientation of the user's head to display a viewer-centered perspective onto the frame-sequential stereoscopic display.

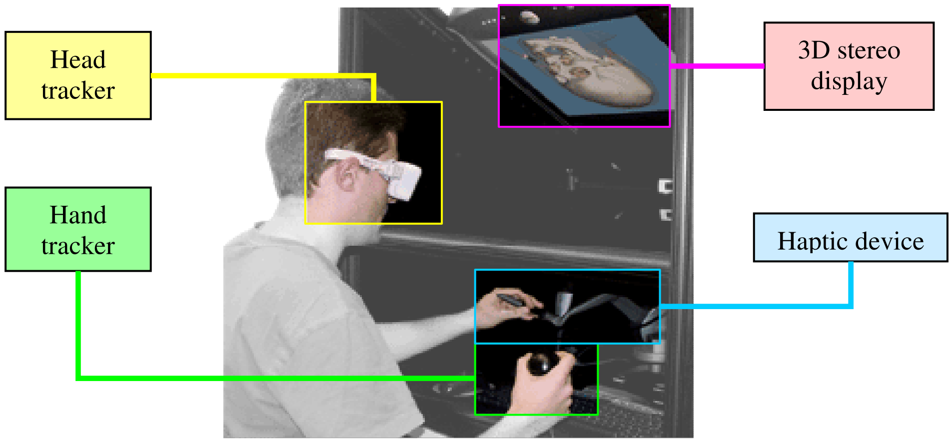


Figure 28. The *ImmersiveTouch*® simulation system.

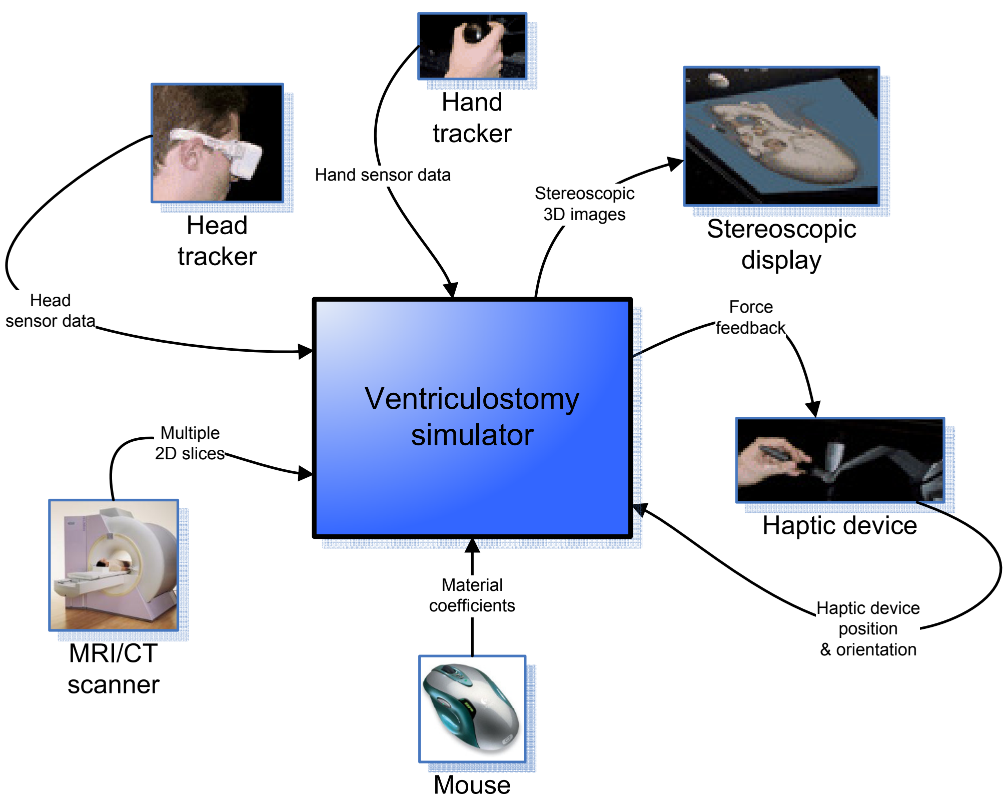


Figure 29. Hardware/software integration for the ventriculostomy simulation.

6.2 Major software modules of the *ImmersiveTouch®* system

The ventriculostomy simulator consists of six interconnected modules, as shown in Figure 30:

- **Medical imagery pre-processing:** MRI and/or CT DICOM data sets are gathered and stripped of all identifying personal data. These are segmented and combined to create a 3-D virtual volume of the patient's head. The three-dimensional, polygonal isosurfaces corresponding to the skin, bone, brain, and ventricles are extracted from the 3-D volume, optimized for haptics rendering and stored in the "3D models" file. Three orthogonal views (axial, sagittal and coronal) of the original MRI/CT scan data showing the ideal targets are then stored in the "MRI/CT images" file, for display while performing the ventriculostomy.
- **Haptics rendering:** This module reads the 3D position and orientation of the haptic stylus, computes collision detections between the virtual catheter and the extracted 3D isosurfaces, and generates the corresponding force feedback. Each isosurface is assigned different haptic characteristics. As a result, the surgeon can feel the different surfaces and textures of the skin, bone, and brain. A viscosity effect is felt as the catheter passes through the gelatinous parenchyma of the brain. As soon as the catheter breaks the dense ependymal ventricular lining, the viscosity effect ceases, providing the surgeon with a distinct "popping" sensation.
- **Material adjustment:** A graphical-user-interface (GUI) displays a control panel with sliders that allows an experienced surgeon to interactively define the values of the haptic material coefficients (stiffness, viscosity, static friction and dynamic

friction) by personal experience to simulate real tactile experience during the surgical procedure.

- **Tracking:** The electromagnetic sensor attached to the shutter glasses tracks head movements to compute the viewer's perspective while the surgeon moves his or her head around the virtual patient's head to locate the landmarks. Another sensor located inside the SpaceGrips tracks the surgeon's hand to define a cut-away plane and a light source to better display the virtual head volume and its virtual contents.
- **Performance scoring:** Once the trainee believes he/she has reached the ideal target with the virtual catheter, this module computes the score based on the distance between the tip of the catheter and the position of the ideal target (e.g. the foramen of Monro). The score is then visualized on the screen.
- **Graphics rendering:** The virtual environment is organized with a virtual patient head displayed using the previously stored 3D isosurfaces. This module displays a stereoscopic perspective of both surgeon's eyes according to position and orientation of his or her head. An infrared emitter coordinates the 3D goggles for each eye with the frame-sequential stereoscopic display.

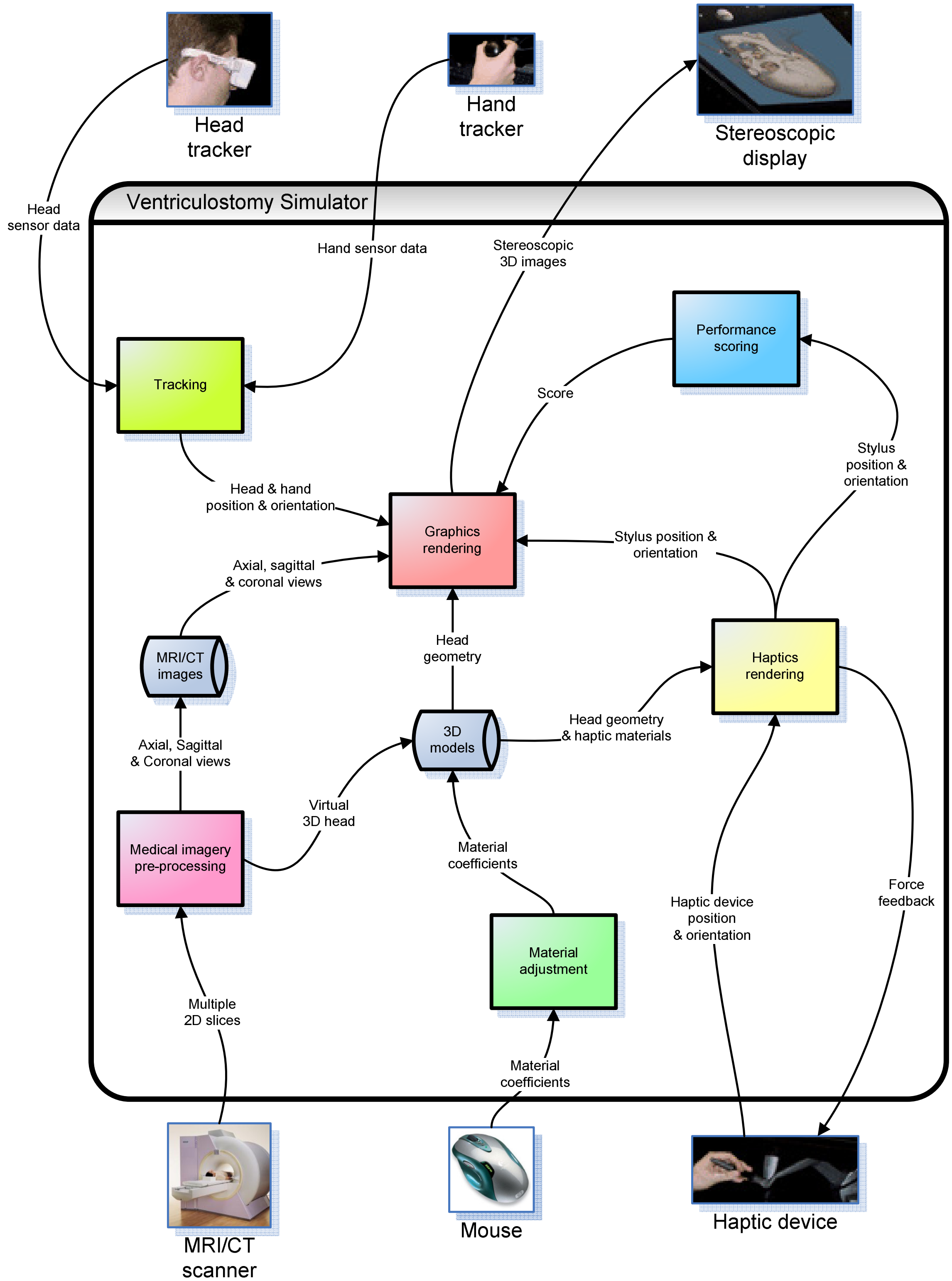


Figure 30. Interconnected modules of the ventriculostomy simulator.

6.3 Medical imagery pre-processing

Figure 31 shows the methodology developed to convert the original DICOM images from the MRI/CT scanner to 3D polygonal models that can be used by the simulator. This pre-processing is done using multiple applications such as ITK-SNAP, (Kitware) ParaView and (Autodesk) 3DStudioMax as described by Rizzi et al. (2007).

ITK-SNAP 1.4.1 provides a friendly user interface by which the user guides the segmentation process in a semi-automatic manner. Series of DICOM images are read into the application. Orthogonal axial, coronal, and sagittal planes are displayed (Figure 33). The user can adjust the image histogram to enhance the visualization and contrast of the anatomical part under study. These views are exported as PNG images and will be shown during ventriculostomy simulation to indicate position of ideal targets to the trainee (Figure 61).

As the first step in segmentation, the volumetric region on which to perform the segmentation is selected. Input images have to be preprocessed before being fed into the segmentation algorithm. ITK-SNAP provides two methods for image preprocessing: Intensity Regions and Image Edges. In our case, Intensity Regions is the method that gives best results. Essentially, the method consists of applying a threshold function to the input images. Two probability fields are estimated: the probability that a pixel in the image belongs to the structure, and the probability that the pixel belongs to the background. The active contour is attracted to the points where both probabilities are equal (Yushkevich et al., 2005).

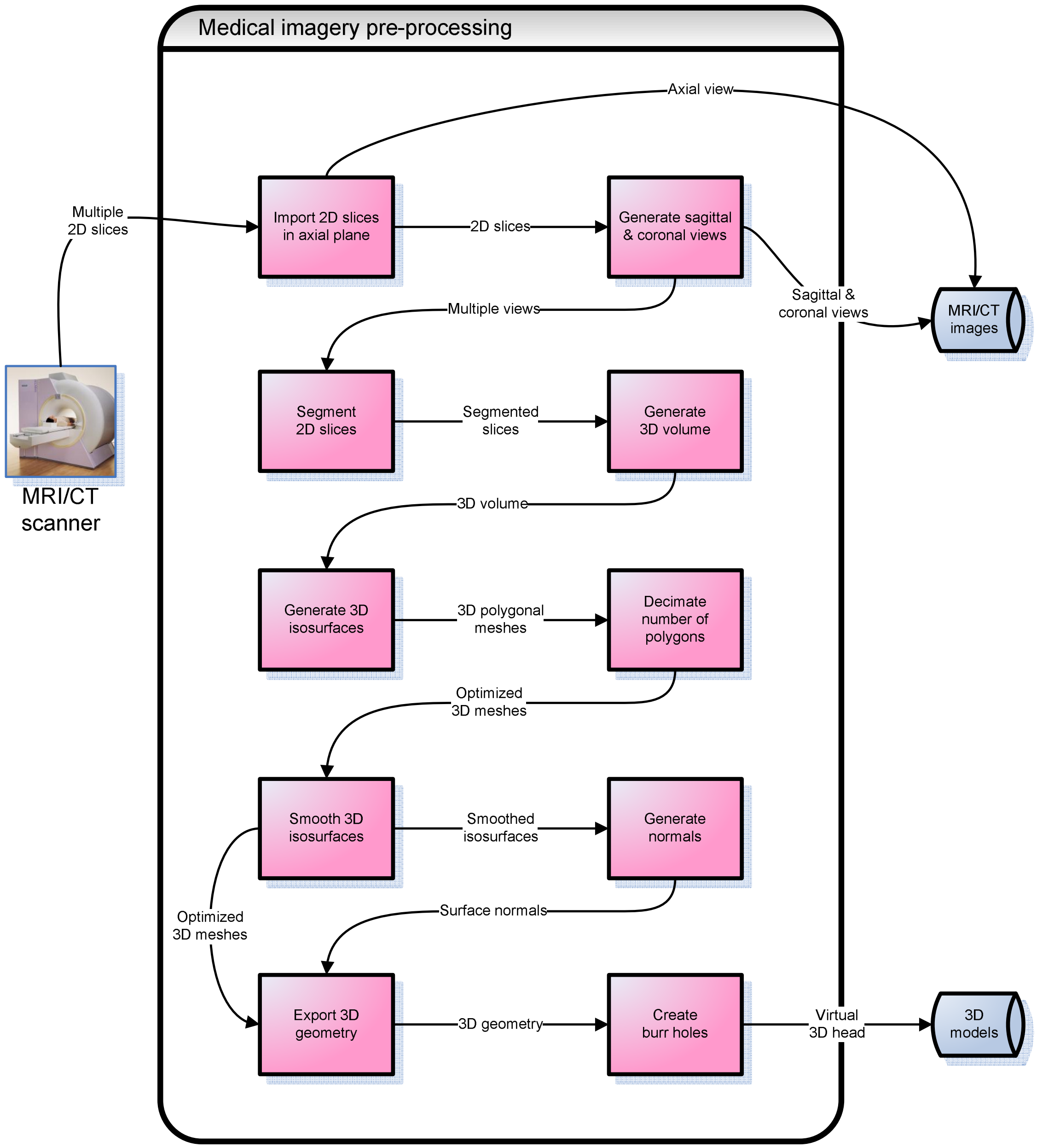


Figure 31. Medical imagery pre-processing module.

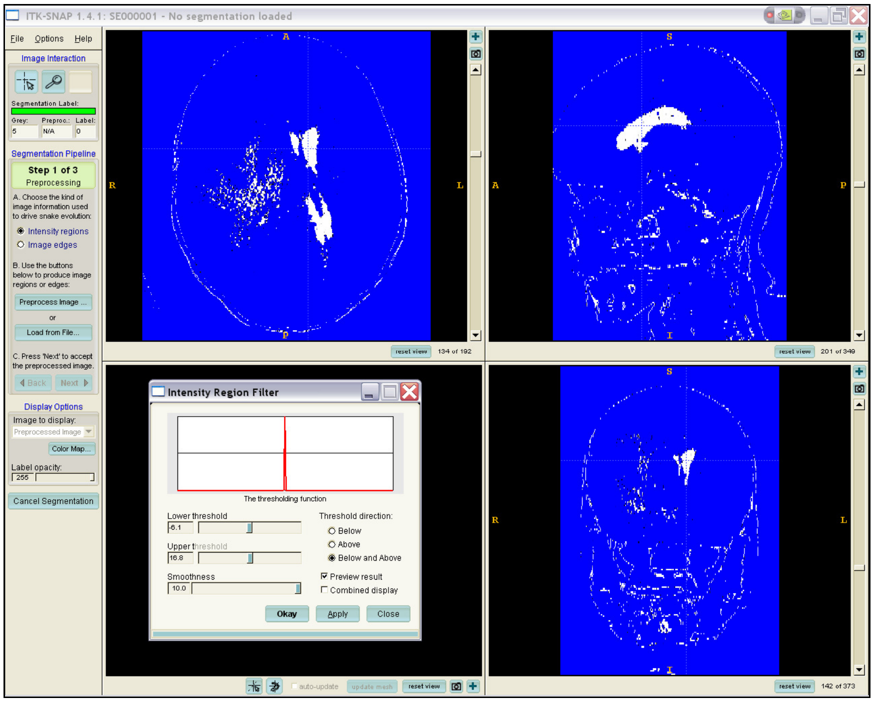


Figure 32. Intensity regions of ventricles.

Figure 32 shows an example of the resulting intensity regions for ventricles. There is a substantial amount of noise artifacts on the left side (top left view). Initially, the user must place 3D spheres of variable radius - called "bubbles" - as starting values for the algorithm. Afterwards, the active contour evolves continuously in each iteration, eliminating great part of the original noise. Once the results of the segmentation are acceptable, the segmentation process is stopped and the segmented volume is saved. Figure 33 shows the final results of the segmented ventricles as well as their 3D isosurface. At this stage, the result of the segmentation process is a set of binary 2D images in which each pixel is white if it corresponds to the segmented region or black otherwise. The process is repeated for each different layer that needs to be extracted from the volume (skin, skull and brain). As an example, Figure 34 shows the segmented skull.

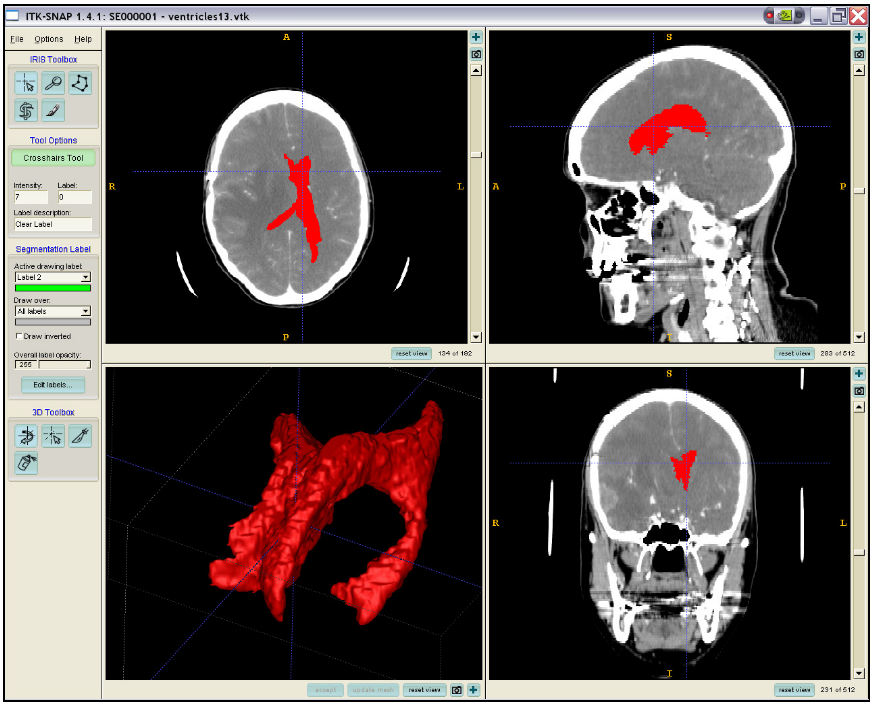


Figure 33. Ventricle segmentation.

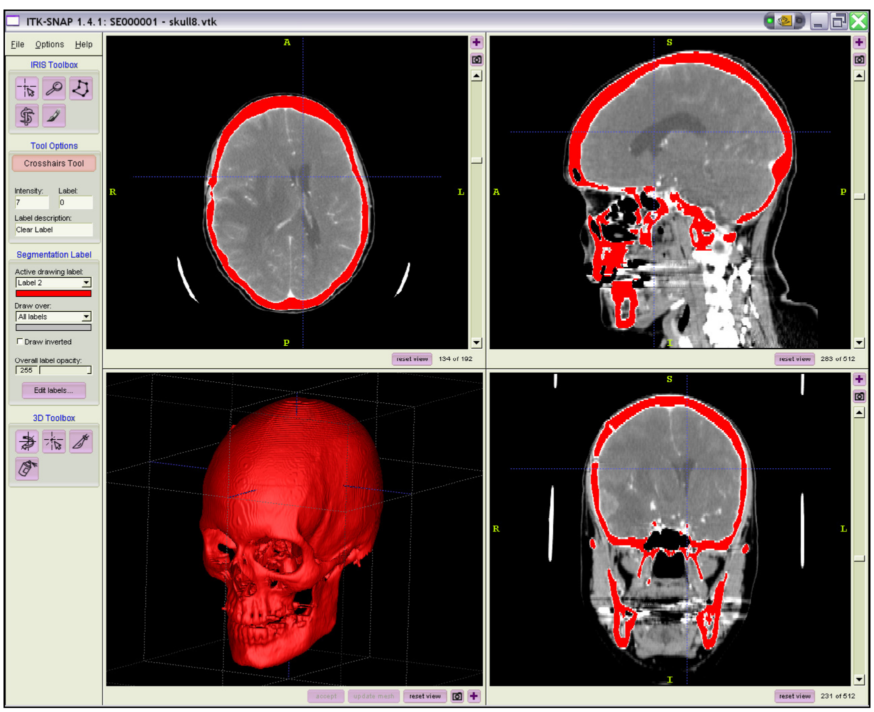


Figure 34. Skull segmentation.

The 3D isosurfaces created by ITK-SNAP (version 1.4.1) are for internal use only, as they cannot be exported. Therefore, another application called ParaView, which is a graphical wrapper of the VTK library, is used. By taking advantage of a set of VTK filters, an optimal 3D polygonal mesh that can be handled by the simulator in real time is constructed. The vtkPDataSetReader filter reads the binary images segmented in ITK-SNAP and creates a volumetric dataset.

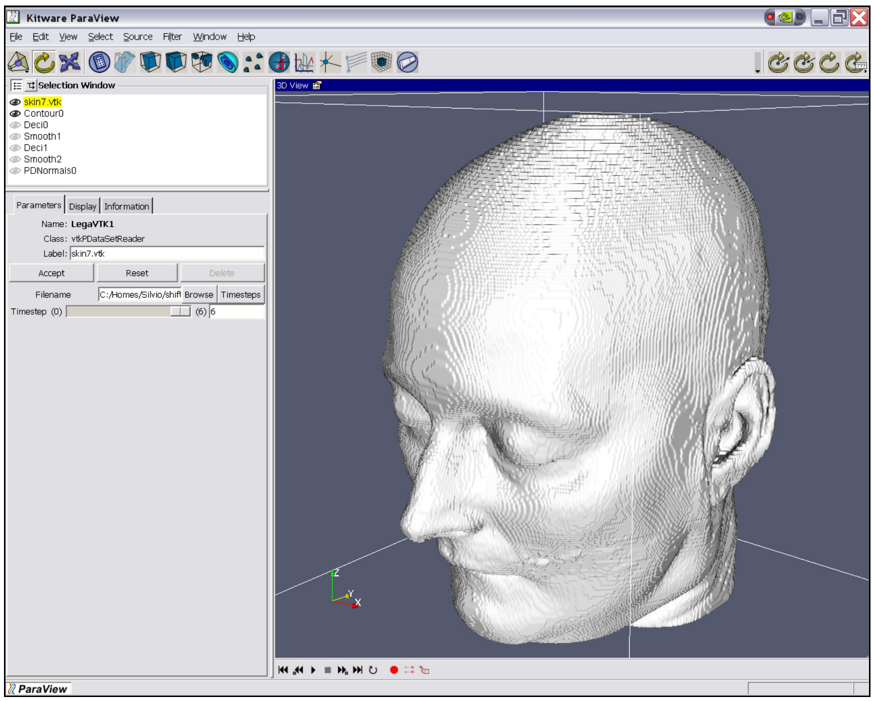


Figure 35. Skin isosurface.

The vtkContourFilter generates a polygonal isosurface from its input data using the Marching Cubes algorithm (Lorensen and Cline, 1987). Figure 35 shows a rough isosurface of the skin as generated by ParaView. The isosurface must be drastically decimated to reduce its number of polygons about 95%; otherwise the haptics library will not be able to render at interactive frame rates (about 1 kHz). A vtkDecimatePro filter is used with the option "preserve topology" activated. The degree of decimation is determined by visually inspecting the density of polygons in the resulting polygonal meshes. Figure 36 exemplifies a polygonal mesh obtained from a brain model which could be further decimated without significant loss of information.

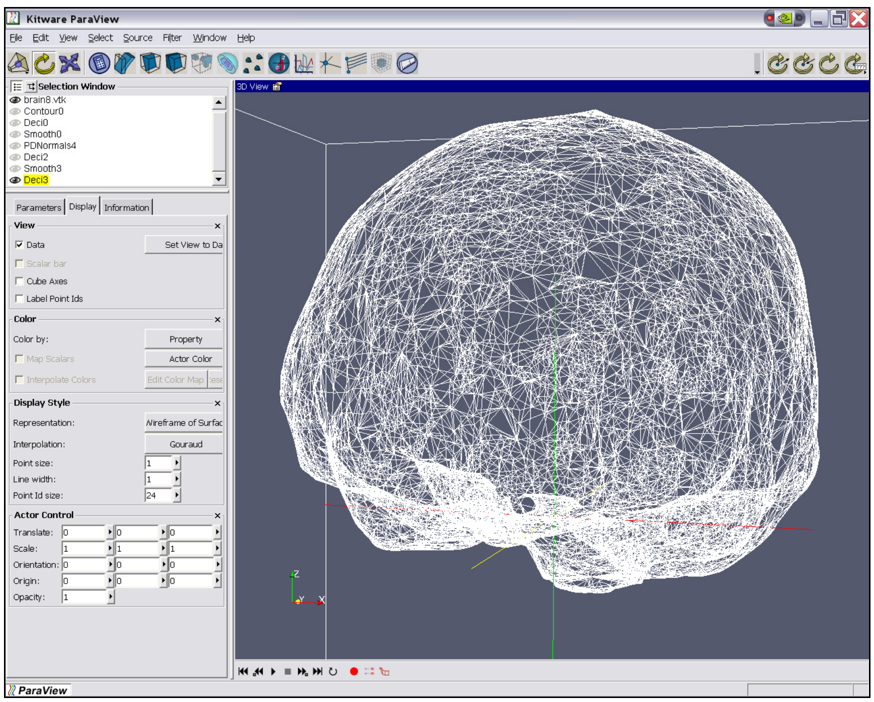


Figure 36. Partially decimated polygonal mesh of the brain.

Following decimation, a smoothing filter is applied using vtkSmoothPolyDataFilter. The number of iterations required for each model was determined observing the smoothness of the model. A vtkPPolyDataNormals filter is applied to generate normal vectors for each polygon. This step is essential for correct graphics and haptics rendering of the 3D models. Finally, the 3D polygonal mesh is saved in STL (Stereo Lithography) format using the vtkSTLExporter filter. Figure 37 shows the 3D model of the skin after the processing done in ParaView.

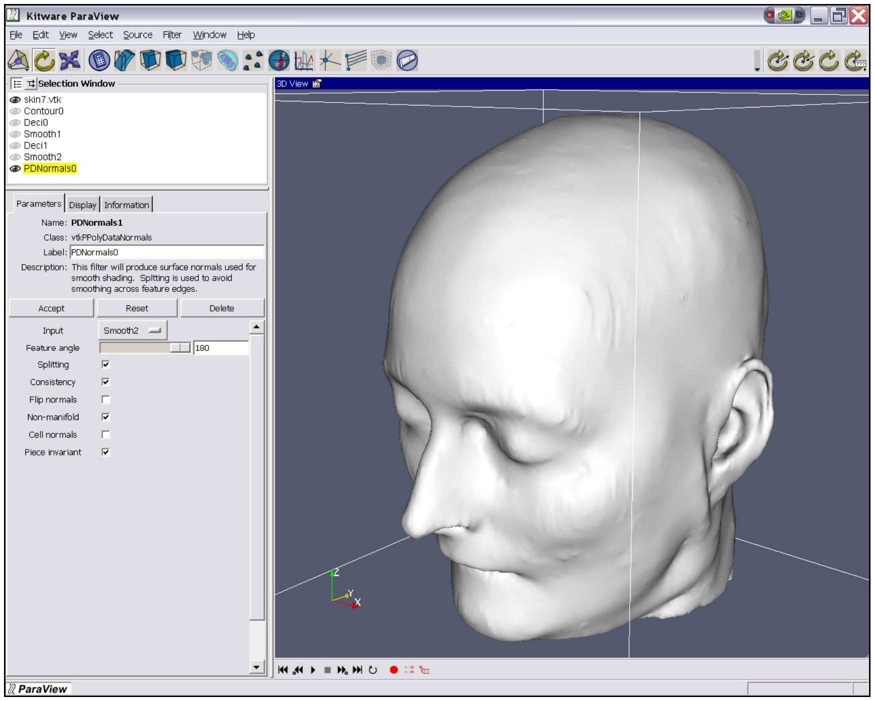


Figure 37. Skin polygonal mesh optimized for haptics rendering.

As a final step, 3DStudioMax is used to create the burr holes in the skin and skull 3D polygonal meshes, combining cylinders and ellipsoid-like shapes with the original model through Boolean operations (Figure 38). A boolean(-) operation is performed between the skin model and the ellipsoid-like shapes. Similarly, a boolean(-) operation is also performed between the skull model and the cylinders. 3DStudioMax is used to edit color, lighting and texture mapping of the polygonal meshes for a more realistic graphics rendering. Finally, the meshes are exported and saved to the “3D models” files in VRML format. Different views of the final 3D models of the virtual head are shown in Figure 39.

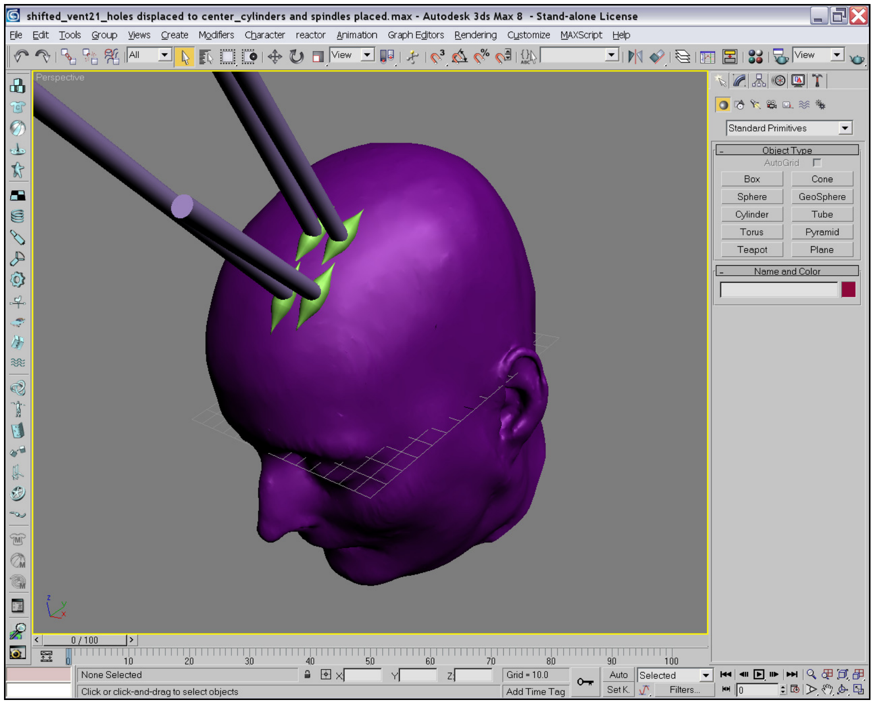


Figure 38. Generation of burr holes.

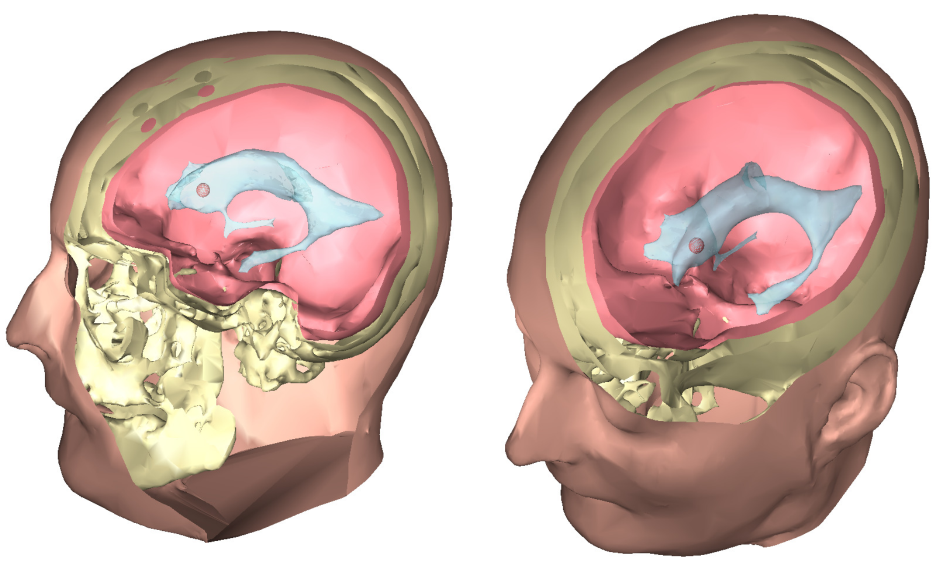


Figure 39. Final model of the virtual patient’s head.

6.4 Haptics rendering

The haptics rendering module (Figure 40) reads the 3D position and orientation of the haptic stylus and checks for point-based collisions between the tip of the virtual catheter and the polygonal models read from the "3D models" file. Once a collision is detected the haptics library computes the proxy or surface-contact point. If there is no collision, the haptic device position is the same as the proxy position. The stylus (device and proxy) position and orientation are then sent to the graphics rendering module to display the virtual catheter on screen, and to the performance scoring module.

While the user manipulates the virtual catheter with the haptic device, the simulator detects if there is a collision with the skin, the skull, the brain or the ventricles. As the catheter passes through the brain, a viscosity effect is activated to simulate the resistance of the gelatinous brain parenchyma. This viscosity effect generates a haptic force that is proportional to the velocity of the haptic stylus and has opposite direction to the movement of the haptic stylus. In the real ventriculostomy procedure, the catheter must be inserted in the brain following a straight-line trajectory from the burr hole towards the ventricles. While the catheter is being inserted, lateral movements are not possible because of the brain resistance. This physical constraint is simulated by locking the orientation of the virtual catheter and activating a penetration-line effect, which forces the user to move the haptic stylus along the current direction, thus following a straight line. This simple haptic effect has proven to be very efficient in terms of processing time and gives realistic results according to feedback received from experienced neurosurgeons. When the user breaks the dense ependymal ventricular lining, the viscosity effect is deactivated to simulate the lack of resistance of the spinal fluid in the ventricles and to provide the surgeon the distinct “popping” sensation. Finally, the haptics library computes the reaction force applied by the touched 3D geometry corresponding to each isosurface and sends the force vector to the haptic device to be felt by the user.

The haptics rendering module has been implemented using the General Haptic Open Software Toolkit (GHOST), a cross-platform haptics library commercialized by SensAble Technologies.

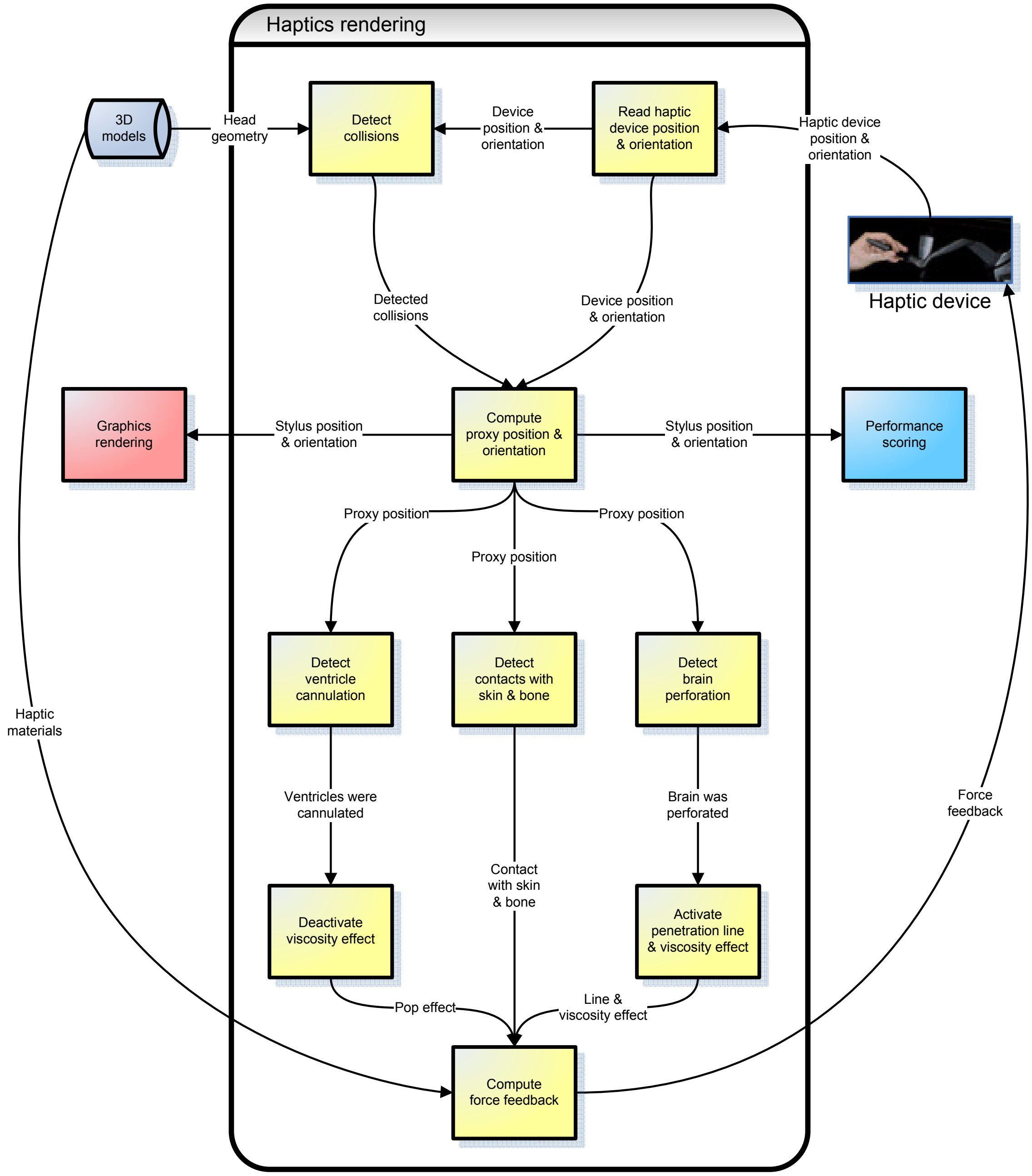


Figure 40. Haptics rendering module.

6.5 Material adjustment

Each 3D isosurface corresponding to the skin, bone, brain and ventricles is assigned different haptic materials, which are defined by four coefficients: stiffness, viscosity, static friction and dynamic friction. The simulator allows neurosurgeons preparing a training session to fine-tune the values of these coefficients to simulate realistic (or even unrealistic) haptic experiences. Increasing the viscosity of the virtual brain until the trainees are able to identify the point where they cannulate the real ventricles has proven to be a very useful tool for training purposes. Once the trainee becomes familiar with the "popping" sensation, the value of the brain viscosity can be decreased to normal values to simulate the real experience.

Rigidness and friction of the skin and bone, as well as amount of force needed to penetrate the brain are some examples of characteristics of haptic materials that are adjusted by this module (Figure 41). Graphic properties such as transparency can also be adjusted. Making the skin, skull and brain transparent allows trainees to improve their eye-hand coordination and help to acquire a mental representation of the 3D anatomy of the patient's brain and ventricles.

Figure 42 shows the control panel window that allows expert neurosurgeons to define the haptic and graphic material properties of the virtual models. The haptics button enables or disables haptic feedback for each 3D isosurface. The control panel has been implemented using the Fast Light ToolKit (FLTK), a small and modular freely-available cross-platform C++ GUI that supports 3D graphics via OpenGL® and its built-in GLUT emulation.

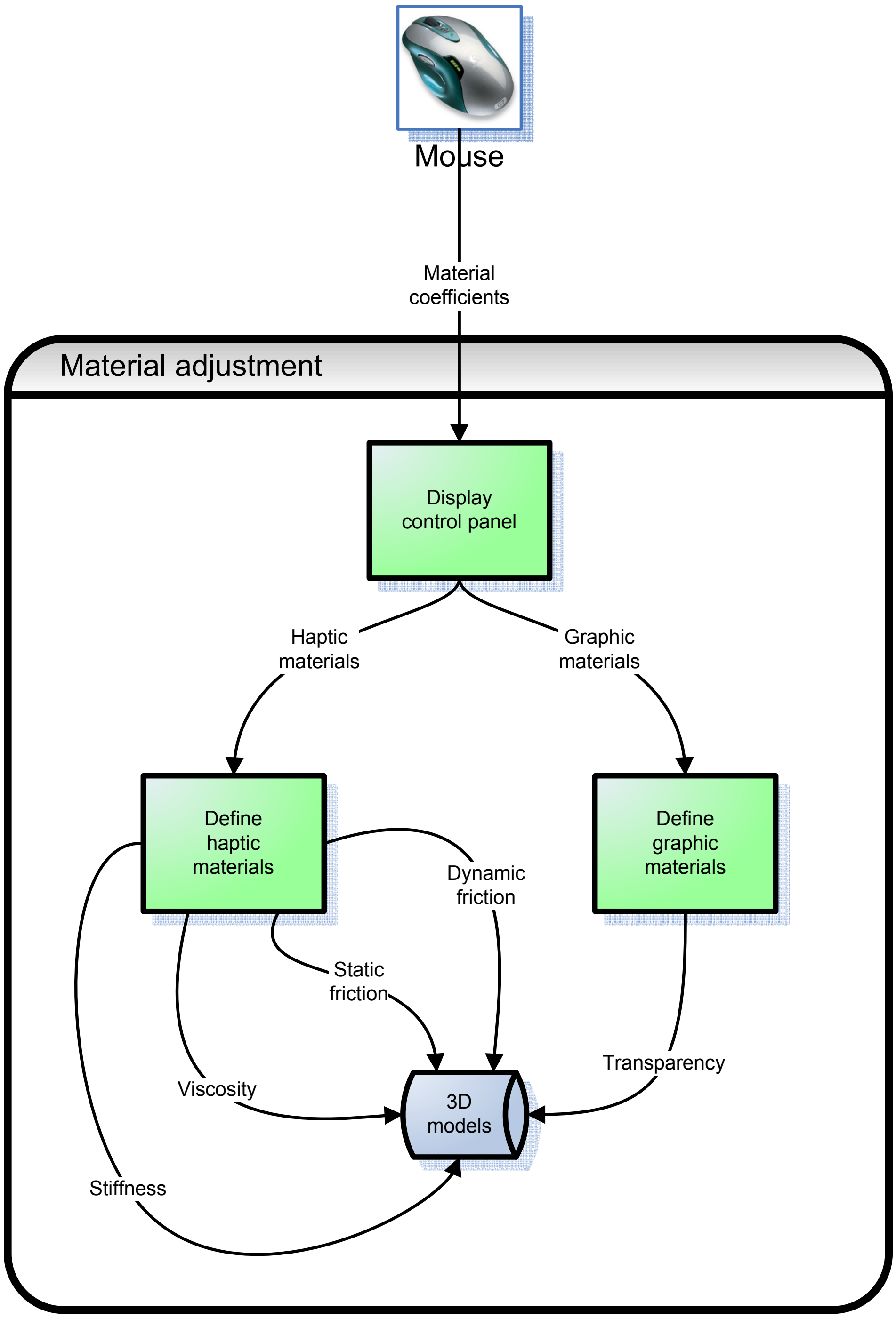


Figure 41. Material adjustment module.

Figure 42. Control panel.

6.6 Tracking

The simulator is compatible with multiple electromagnetic tracking devices from Ascension Technologies Corp. (pciBIRD, Flock of Birds, miniBIRD, driveBAY, trakSTAR, and medSAFE). This module (Figure 43) detects the connected tracking device and communicates with it to track the 3D position and orientation of the surgeon's head and hand. The tracking measurement rate is set to 85 Hz to minimize interference with the CRT monitor, whose vertical refresh rate is 100 Hz. With the exception of Flock of Birds, all tracking devices are handled by the pciBIRD API. If the Flock of Birds is connected, it is handled by standard serial port communication.

Due to the fact that a CRT monitor is used, the data obtained by the tracker must be processed by a low pass and smoothing filter to eliminate possible jittering caused by electromagnetic interference with the CRT. The head position and orientation is sent to the graphics rendering module to map the virtual perspective camera to the stereo goggles and render a correct viewer-centered perspective. The hand position is also sent to the graphics rendering module to manipulate the virtual tools (light source and clipping planes).

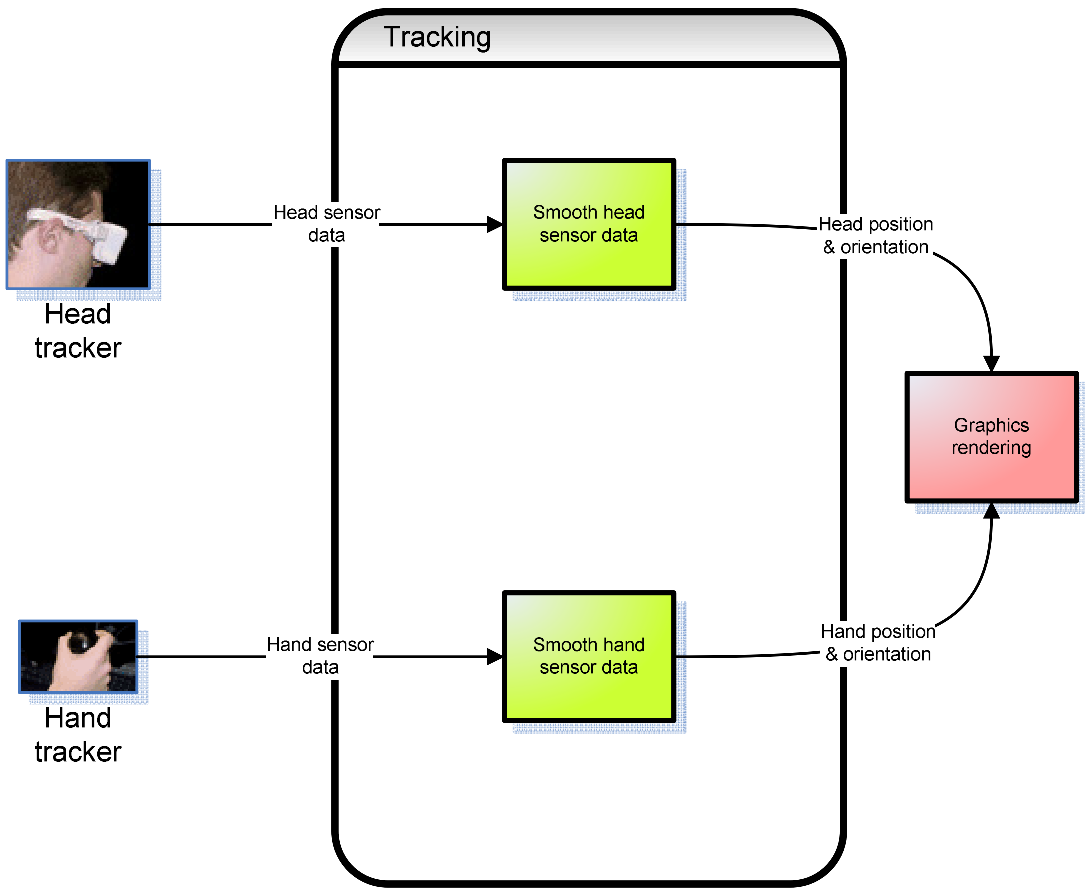


Figure 43. Tracking module.

6.7 Performance scoring

The simulator allows one to define certain landmarks (or widgets) that are used to measure the trainee's performance. These landmarks are the burr holes, the targets (e.g. the foramen of Monro) and the midline plane. When multiple burr holes and targets are specified, the simulator is able to automatically identify the target that corresponds to the chosen burr hole. These landmarks can be interactively defined by an experienced neurosurgeon manipulating the haptic device. They are saved in their respective files (Figure 44).

After the trainee has inserted the catheter during the virtual ventriculostomy, the simulator uses the previously defined landmarks to compute the catheter depth and performance score. The catheter depth is the distance from the burr hole to the tip of the catheter. The performance score is based on the distance from the tip of the catheter to the ideal target. The simulator also determines if the catheter insertion was ipsilateral (it remained in the same brain hemisphere) or contralateral (otherwise) based on the midline plane. This information, along with the current stylus position and orientation, is saved into the "Report" file for further statistical analyses. The final score is sent to the graphics rendering module to be displayed on the screen.

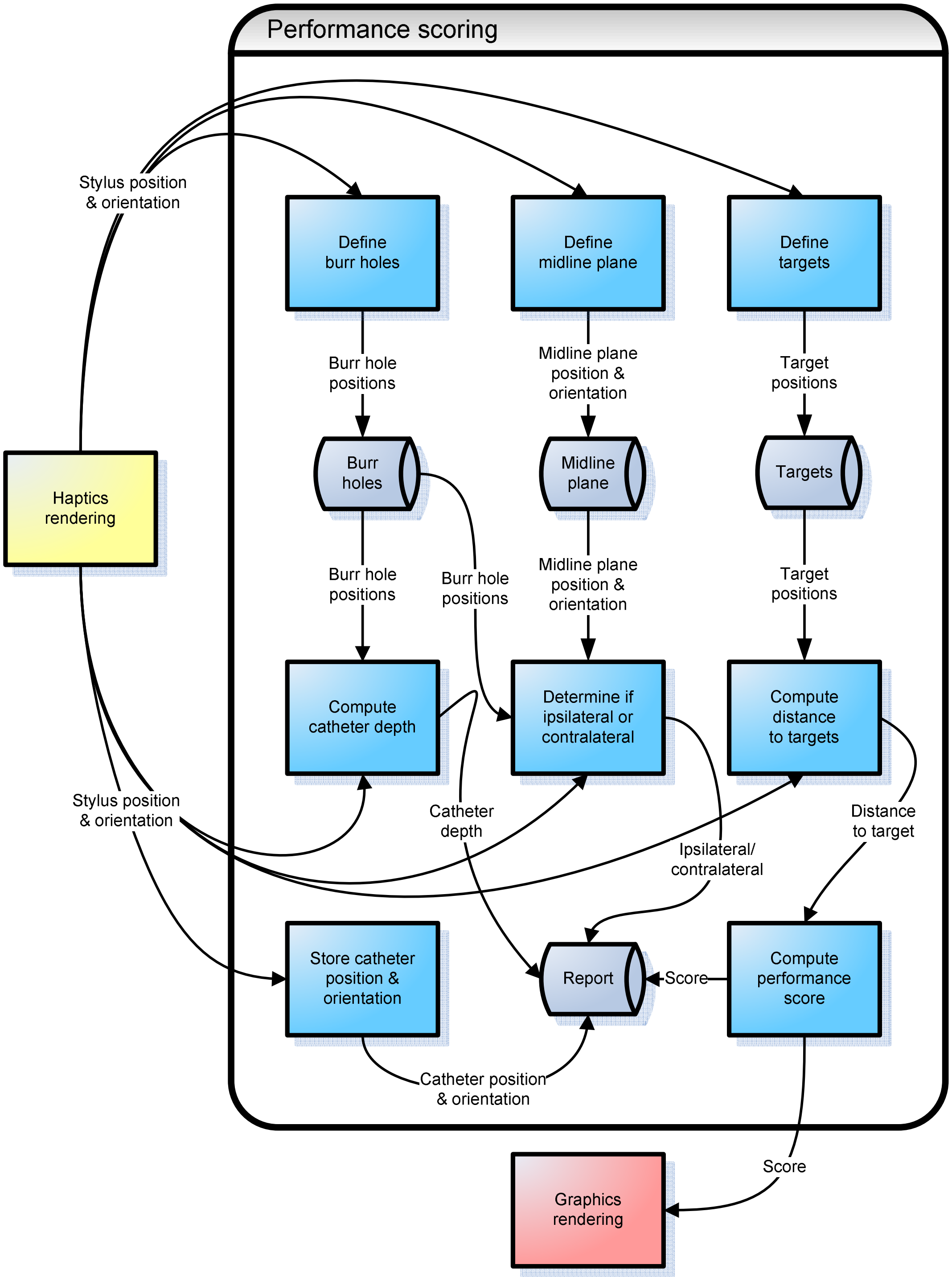


Figure 44. Performance scoring module.

6.8 Graphics rendering

Coin3D (SystemsInMotion), an open-source implementation of Open Inventor, is a high-level 3D graphics library that organizes 3D objects as a scene-graph structure. Implemented on top of OpenGL, Coin3D is highly optimized for fast real-time polygonal rendering. The graphics rendering module traverses the scene graph that contains the 3D isosurfaces, the virtual catheter, and three orthogonal views of the MRI/CT images, as well as the virtual light, the cutting plane manipulator and the score indicator (Figure 45).

The head position and orientation, given by the tracking receiver attached to the stereo goggles, is used to compute the viewer-centered perspective projection onto the virtual projection plane. Unfortunately, Coin3D does not provide any native camera node that can handle this kind of off-axis frustum. However, it is flexible enough to allow the programmer to create custom nodes. An extension of the native SoPerspectiveCamera node has been implemented (in OpenGL) to properly render both left and right views. The implementation is based on the work done by Pape et al. (1999) for the CAVELib™ to project the viewer-centered perspective on each CAVE walls, except that our virtual projection plane is at 45º.

The hand position and orientation given by the SpaceGrips allows manipulating the light source and the clipping planes in the 3D workspace. The position and orientation of the virtual catheter are updated with the current haptic stylus information. The user can position the virtual patient's head by manipulating the haptic stylus while pressing the haptic device button. Once the surgeon has inserted the catheter, pressing a button on the SpaceGrips will freeze the catheter and the score will be displayed on the screen.

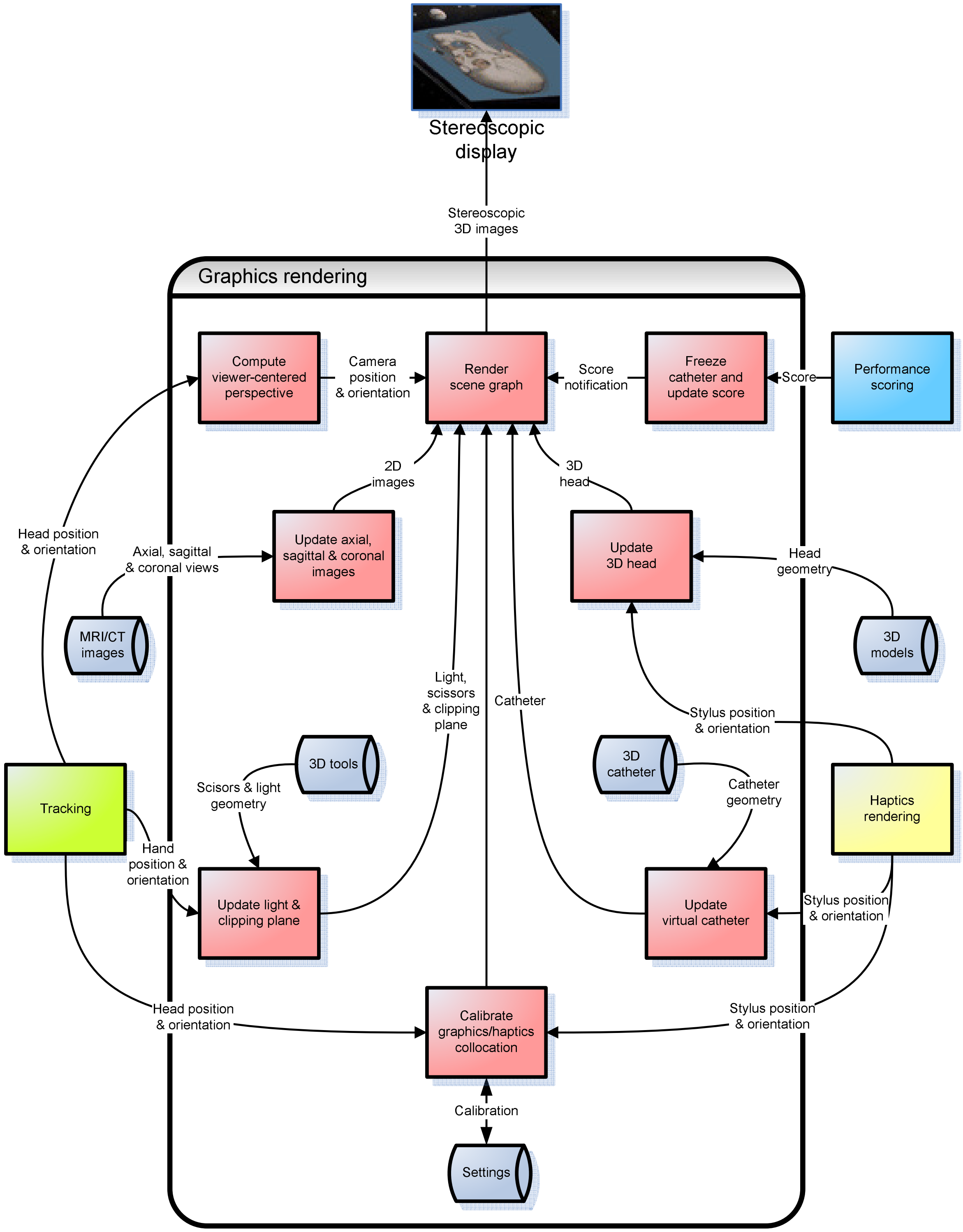


Figure 45. Graphics rendering module.

6.8.1 Calibration of graphics/haptics collocation

ImmersiveTouch® includes many elements that must be calibrated to provide a correct graphics/haptics collocation. The virtual projection plane and the haptic workspace need to be expressed in terms of the tracking coordinate system, whose origin is located in the transmitter. Since we can measure the size of the physical screen, we know the dimensions of the virtual projection plane. From the fundamental design constraint, we also know that the projection plane orientation is at 45º. Then, we should measure the distance from the center of the projection plane to the transmitter. Since the projection plane is just the reflection of the monitor screen, a physical measurement would be cumbersome to obtain. Instead, we take advantage of the tracking system, with which we obtain the required measurement by simply holding a tracking sensor (receiver) at the center of the virtual projection plane until it is superimposed with a point displayed at the center of the screen. Then, the position given by the tracking system is the measurement sought.

The measurement of the offset from the center of the haptic workspace to the transmitter is done by interactively moving the haptic stylus and leaving the graphics rendering fixed until the haptic stylus coincides with the virtual probe. This is done for only one 3D point in the collocated workspace. However, for a non-linear calibration, we could repeat this procedure at many points in the haptic workspace to create a correction table as done by Czernuszenko et al. (1998).

The interocular distance, and the offset from the head sensor to the center of the head, as well as the offset from the hand sensor to the center of the SpaceGrips® are manually specified in the "Settings" text file, similar to the CAVE™ and ImmersaDesk™ applications.

6.9 Chapter conclusions

We have discussed how a second-generation ventriculostomy simulator has been developed on the *ImmersiveTouch*® system. The software design and implementation of the simulator have been organized in six major processing modules that seamlessly integrate the following third-party applications and programming libraries:

- ITK-SNAP 1.4.1 for volume segmentation of medical imagery
- ParaView 2.4.4 for isosurface generation and optimization of polygonal meshes
- 3DStudioMax 5.0 for burr hole creation and realistic graphical appearance
- Coin3D 3.0 for interactive graphics rendering
- GHOST 4.0 SDK for haptics rendering
- pciBIRD API for head and hand tracking
- FLTK for low-level OpenGL interface and graphical user interface

An efficient combination of stereoscopic 3D visualization with dynamic perspective tracking, realistic haptic feedback, and perfect collocation of real and virtual objects allows this ventriculostomy simulator to overcome the limitations of previous developments.

7. GPU ALGORITHM FOR REAL-TIME ELASTIC DEFORMATION

7.1 Introduction

Haptic interaction along with elastic object deformation has been useful for learning many surgical procedure simulations (Hanson et al., 2004) (Koyama et al., 2000) (Wang et al., 2006). Virtual human organs are deformed by the contact forces generated from medical instruments. It is well known that realistic simulation of physically-based deformation of elastic objects is very challenging because of the complex computations to be performed in real time. However, a simple spring-damper model can be adequate for achieving a relatively realistic deformation for real-time interactions.

Current haptics libraries, such as GHOST and OpenHaptics, implement a spring-damper model to allow a point-based force-feedback interaction with 3-DOF haptic devices such as the PHANToM Desktop, Omni, and Premium 1.0. For point-based haptic applications, only the tip of the haptic stylus interacts with virtual objects. In each frame, a collision detection algorithm checks if the Haptic Interaction Point (HIP) is inside the virtual object. If so, penetration depth is computed as the distance between the current HIP and the corresponding Surface Contact Point (SCP). Based on a spring-damper model at the contact point, the haptics library computes the reaction forces that are proportional to the penetration depth. The more the user penetrates the object, the higher the reaction forces applied by the haptic device (Zilles and Salisbury, 1995).

Even though the spring-damper model implemented by the haptic library allows the user to feel the object resistance at the contact point, there is no explicit deformation of the object geometry. Therefore, the graphics rendering does not show any object deformation at all. The goal of this work is to enhance the user's experience by rendering a coherent graphics deformation of the virtual objects colliding with the haptic probe without compromising the current haptics frame rate.

7.2 Related work

CPU-based deformation with haptics: In terms of elastic deformation, James and Pai, (2001) implemented a physically-based simulation algorithm using pre-computed Green's functions and Capacitance Matrix Algorithms to render object deformation. Haptics rendering is done by GHOST with the undeformed model. Webster et al. (2001) developed a suturing simulator based on a mass-springs grid of dynamic vertices to model a flat 3D mesh whose vertices can be displaced by a virtual pair of scissors. Choi et al. (2003) proposed a deformable model based on a similar mass-spring grid and a force propagation process to perturb the vertices around the contact point. Duriez et al. (2006) implemented an implicit multi-contact deformation algorithm that solves Signorini's and Coulomb's laws with a fast Gauss-Seidel-like method obtaining haptic frame rates of 250Hz. Even though these previous works were successful to render interactive deformation with 3D meshes of fewer than 700 vertices, they cannot be extended to complex geometry without affecting the haptics performance, because the CPU power must be shared between the haptics rendering and the graphics deformation.

GPU-based deformation without haptics: In the last few years the use of GPU has proven to be an effective solution to general purpose problems. In the field of interactive elastic object deformation, Mosegaard and Sørensen (2005) developed two methods to model a spring-mass system for complex geometry taking advantage of the parallel processing of the GPU. Since the simulation is done exclusively on the GPU, the CPU is not fully utilized, causing an unbalanced load between CPU and GPU. Randima (2004) proposed an alternative implementation of the mass-spring system on the GPU. Georgii and Westermann (2005) implemented a physics-based deformation that combines a CPU simulation engine with a GPU render engine, achieving a more balanced load. James and Pai (2002) developed another physically-based deformation algorithm with a mesh of 18,000 vertices. However, all these GPU-based deformation methods cannot be seamlessly integrated with polygonal-based haptic applications.

GPU-based deformation with haptics: Sørensen and Mosegaard (2006) modified their GPU-based implementation to incorporate force feedback, achieving a haptic frame rate of 450 Hz deforming 3D meshes of up to 91,000 vertices. Unfortunately, that frame rate is not high enough to minimize haptic discontinuities and instabilities (Lin and Salisbury, 2004). De Pascale et al. (2004, 2005) presented a GPU-based deformation method to achieve both haptics and graphics rendering, implementing a single DOF mass-spring-damper system at the contact point and using shape-functions to distribute the deformation of the closest vertices. Previously implemented algorithms are very useful to incorporate certain haptic feedback to graphics applications with deformation. However, since the primary focus of the applications is graphics performance, they resulted in realistic graphic deformation at the expense of poor haptics performance.

7.3 Approach overview

The goal of this algorithm is to enhance the user's perception of the ventriculostomy simulator by incorporating graphical deformation, while maintaining a 1-kHz haptic frame rate (Luciano et al, 2007).

In most CPU-based haptic applications, a common polygonal geometry is processed by both the CPU (for the haptics rendering) and the GPU (for the graphics rendering). Haptics rendering includes collision detection, computation of forces, and bidirectional communication with the haptic device. Due to the complexity and sequential nature of the haptics rendering, as well as the GPU parallel and vector processing power, the haptics rendering takes longer than the graphics rendering. Therefore, the GPU is underutilized most of the time. If deformation is to be incorporated to the haptic application, it is more efficient to let the CPU deal with the haptics rendering while the GPU computes deformation for the graphics rendering in parallel.

The GPU algorithm focuses on point-based local deformation around the contact point, and thus, global deformation and volume preservation are beyond the scope of this research. The implementation can be thought of as a tradeoff between real-time interaction and sophisticated physics-based realism. Figure 46 shows how the brain tissue is deformed in real time in response to pressure applied by a virtual instrument.

Figure 46. Virtual brain being deformed by the instrument.

7.4 Algorithm

7.4.1 Vertex displacement

GHOST implements a 1-DOF spring-damper model along the normals of the object surface. In this way, it lets the user feel the resistance of the object as the haptic probe makes contact with the object and when it pushes against its surface. Similarly, it is possible to render the object deformation by displacing the vertices along its normals. In the case of point-based haptics rendering, the force feedback calculation is done only at the contact point. However, for graphics rendering we need to compute not only the deformation at the contact point, but also at its neighborhood. To do that, we can take advantage of the vertex shader to displace each vertex in parallel, while the CPU computes the force feedback.

Figure 47 shows how the vertices are displaced along their normals to deform the object surface. The maximum displacement is found at the contact point *C*. Then the displacement decreases non-linearly as the vertices are located farther away from the contact point. The position of the displaced vertex V_j can be simply computed by the vertex shader as:

$$V_j = V_i - N_i * G(d_i)$$

where:

V_j = 3D coordinates of displaced vertex

V_i = 3D coordinates of original vertex

N_i = Normal vector of vertex V_i

$G(d_i)$ = Distribution function

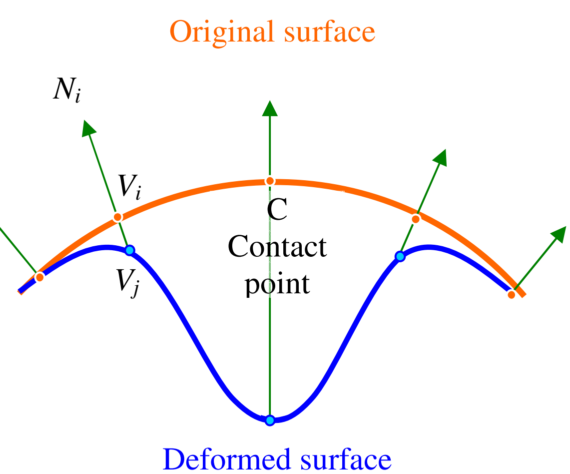


Figure 47. Vertex displacement along its normal done by the vertex shader.

The distribution function $G(d_i)$ defines the amount of displacement for neighbor vertices. It consists of a Gaussian function with zero mean and variance σ^2 (Figure 48), which is computed as follows:

$$G(d_i) = p * e^{\left(-\frac{d_i^2}{2\sigma^2}\right)}$$

where:

p = penetration depth $= \left|HIP - SCP\right|$

HIP = haptic intersection point (device position)

SCP = surface contact point (proxy position)

d_i = Euclidean distance from the contact point to the vertex V_i

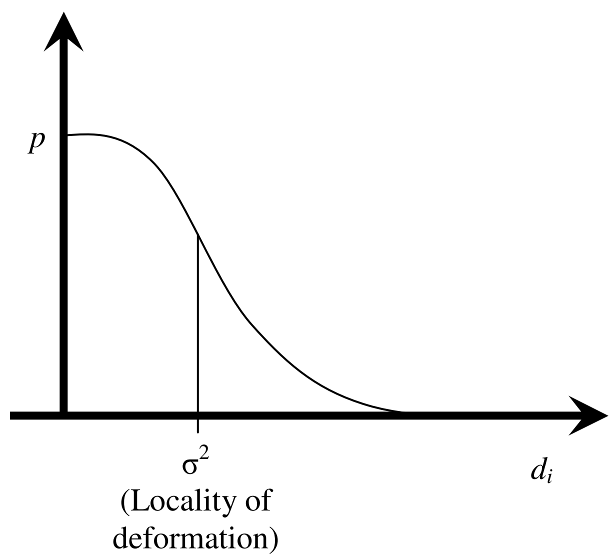


Figure 48. Gaussian distribution defines the deformation profile.

Each vertex shader computes the Euclidean distance from its vertex to the contact point. When that distance is zero, the Gaussian function returns the penetration depth previously computed by GHOST. As we move away from the contact point, the displacement tends to zero, producing a realistic "inverted-bell shape" at the vicinity of the contact point.

The variance σ^2 of the Gaussian function controls the shape of the deformation. A small variance creates a very local deformation affecting only the closest vertices of the contact point, while a large variance produces a more global deformation around a larger area, allowing us to simulate the behavior of different materials. Compare Figure 46 and Figure 49 to see the difference between brain and skin deformations.

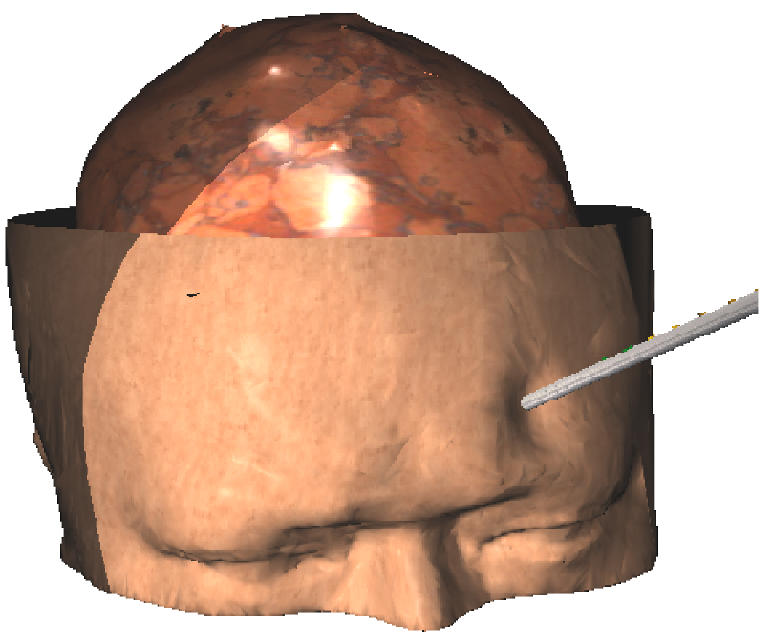


Figure 49. Skin deformation with different variance.

7.4.2 Normal calculation

In order to achieve a realistic rendering of the deformation, it is not only necessary to deform the surface displacing the vertices, but also to re-compute the normals of the deformed surface. This is a crucial step since lighting depends on the surface normals. A naïve approach would be to send all new vertices back to the CPU, let it compute the new normals, and then send the new normals back to the GPU. However, this would lead to a performance bottleneck due to the slow communication from GPU to CPU. Hence this computation needs to be done entirely on the GPU.

The new normals could be computed per vertex on the vertex shader. The fragment shader would then take the new computed normals at the vertices of each triangle and it would interpolate them to obtain the normals at each fragment inside the polygon. However, since we are dealing with a non-structured polygonal mesh, previously decimated to increase the haptics performance, the isosurface has triangles of different sizes. There are flat areas in which the vertex density of the mesh is too low. Therefore, smoother shading is obtained when the normal calculation is performed by the fragment shader.

Previous Jacobian-based GPU-shader algorithms, such as Randima (2004), computed either the inverse of the 3x3 Jacobian matrix, or the tangents and binormals. This step becomes very time consuming if the normal perturbation is done by the fragment shader. The algorithm presented as follows consists of a more efficient alternative.

On the CPU, the normals at each vertex are computed considering the vertices of the neighboring polygons. Unfortunately, the GPU cannot follow the same approach because the fragment shader lacks that information. Thus, a different approach needs to be implemented. Instead of re-computing the normals, the GPU can slightly perturb the old normals to reflect the changes of the deformed surface. The idea is to rotate the original normal N_i at the vertex V_i towards the contact point C by a certain angle θ about a rotation axis W (Figure 50).

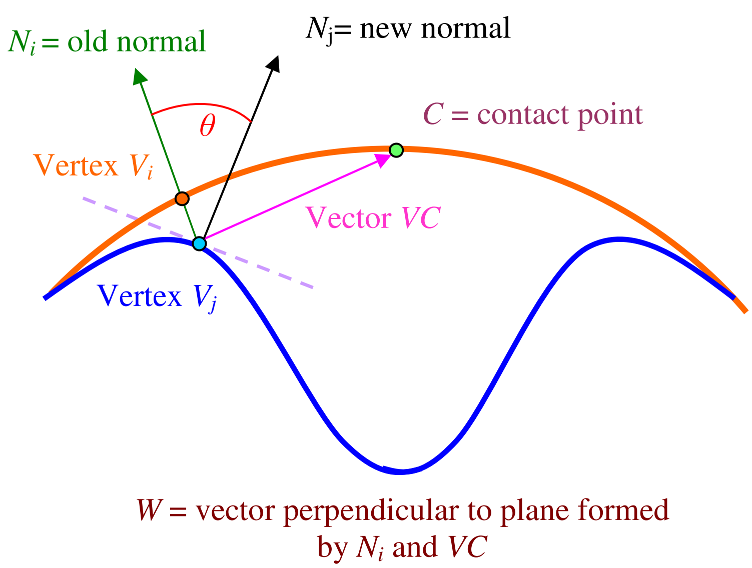


Figure 50. Normal calculation done by the fragment shader.

Vector VC is computed from the new vertex V_j (displaced by the vertex shader) to the contact point C. The rotation axis W (coming out of the page) is defined by the vector perpendicular to the plane formed by the vectors N_i and VC and is computed with the cross product function as:

$$W = N_i \times VC$$

The rotation angle θ depends on the slope of the deformed surface at each vertex V_i or, even more precisely, at each fragment since the normal calculation is performed by the fragment shader. Since the deformed geometry follows a Gaussian function around the contact point, the surface slope at each fragment can be computed as the first derivative of the Gaussian function:

$$G'(d_i) = p * \left(-\frac{d_i}{\sigma^2} * e^{\left(-\frac{d_i^2}{2\sigma^2} \right)} \right)$$

Now the rotation angle θ is simply defined as:

$$\theta = \arctan\left(-G'(d_i) \right)$$

Knowing the rotation axis W and the angle θ, it is very efficient to compute the perturbed normal N_j using the cross and dot product functions as follows:

$$N_j = T + (N_i - T) * \cos(\theta) + (N_i \times W) * \sin(\theta)$$

where:

$$T = W * (N_i \bullet W)$$

Since W is orthogonal to N_i, T is a zero vector and then the perturbed normal N_j is simply reduced to:

$$N_j = N_i * \cos(\theta) + (N_i \times W) * \sin(\theta)$$

It is important to mention that since the geometry deformation and the normal computation need to be consistent, both the vertex and the fragment shaders must compute the Euclidean distance from the vertex to the contact point in eye-coordinate system.

The resulting normals are then used by the fragment shader to render the spot light as well as the directional light achieving a realistic rendering of the elastic deformation.

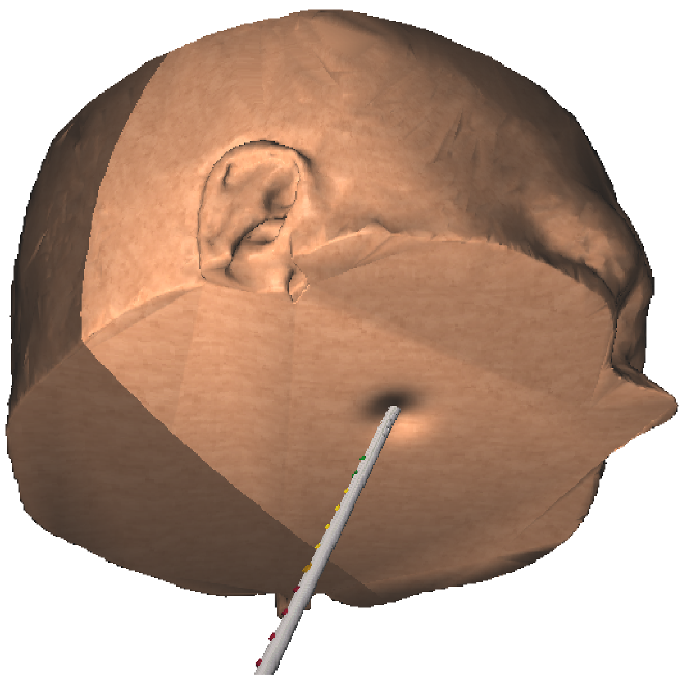


Figure 51. Details of the normal perturbation at a low-vertex-density area.

Figure 51 shows the worst case scenario applying the deformation algorithm on an area of the geometry in which the vertex density is extremely low. The flat surface consists of few large triangles produced by the isosurface decimation process. Here the vertex shader does not displace any vertex at all because all of them are far away from the contact point. However, since the fragment shader computes the normals, it gives the illusion that the surface is properly deformed.

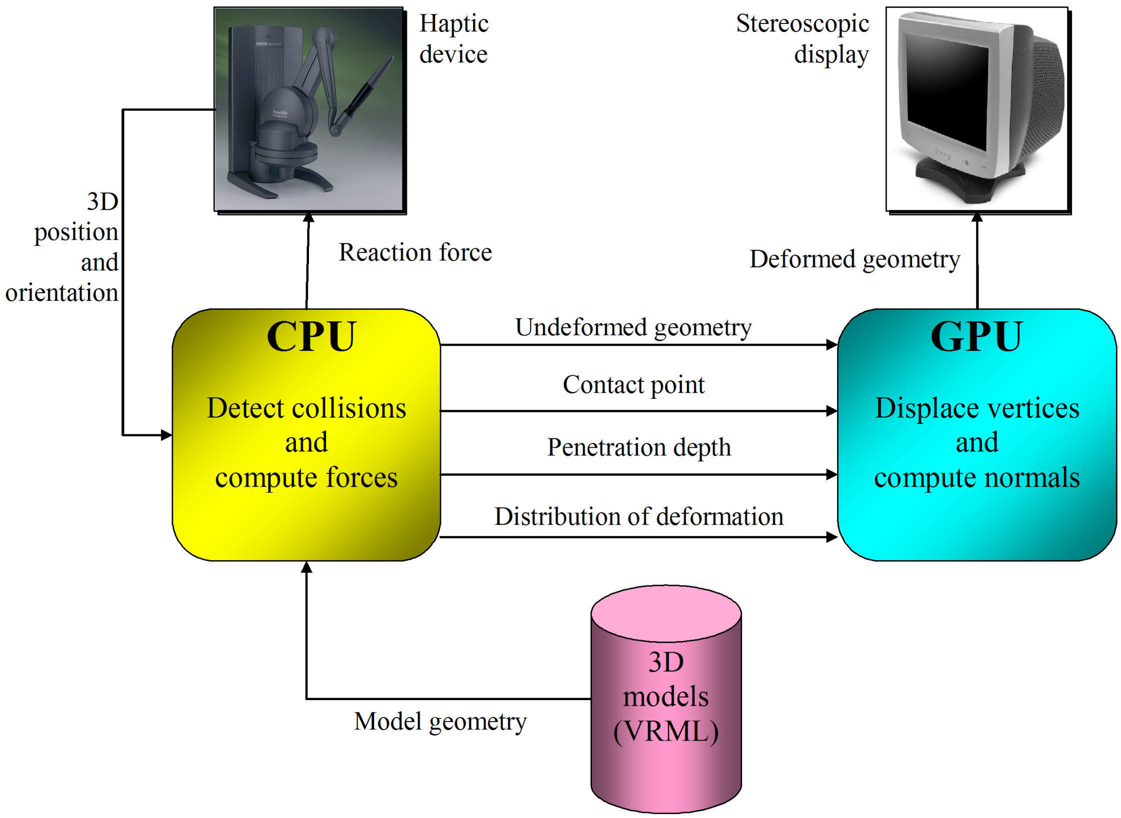


Figure 52. Communication between the CPU and GPU.

7.5 Implementation

Two equivalent scene-graphs are stored in the main memory and handled by two libraries running on CPU: GHOST and Coin3D. A haptic scene-graph is created by GHOST to perform the haptics rendering, and a graphics scene-graph is created by Coin3D to perform the graphics rendering. Coin3D also serves as the communication link between the CPU and the GPU. Figure 52 shows the interaction between the CPU and

GPU, as well as the communication with the haptic device and the stereoscopic display of the *ImmersiveTouch*®.

GHOST and Coin3D run in two separate threads at different speeds, since haptics rendering requires a minimum frame rate of 1 kHz whereas 60 Hz is fast enough for the graphics rendering. GHOST traverses the haptic scene-graph, detects collisions between the haptic stylus and 3D models, and computes the reaction forces to be sent to the haptic device. Concurrently, Coin3D traverses the graphic scene-graph and sends the position of the contact point, the penetration depth, and the distribution of the deformation to the GPU.

The GPU deforms the geometry displacing the vertices around the contact point, and computes the normals of the deformed geometry. The deformation algorithm was implemented in C++ using OpenGL Shading Language (version 1.20) (GLSL) and Coin3D (version 3.0).

7.6 Real-time performance results

Table II shows the performance of the ventriculostomy simulator running the deformation algorithm on a dual Xeon 3.6 GHz Windows PC with nVidia Quadro FX 3400 graphics card. It demonstrates how the algorithm is able to maintain both acceptable graphics and haptics frame rates.

TABLE II

PERFORMANCE RESULTS

3D model	Vertices	Polygons	Graphics FPS	Haptics FPS
Brain	68,856	22,952	61	1000
Skin	90,207	30,069	60	1000
Skin + Brain	159,063	53,021	59	999

Haptics frame rate was obtained by using the gstGetPhantomUpdateRate function in GHOST. Graphics frame rate was obtained by running a simple timing function (Howard and Craven).

7.7 Chapter conclusions

An efficient parallel algorithm for real-time deformation of elastic objects has been designed and implemented on the GPU using OpenGL Shading Language. While the CPU performs the haptic rendering, allowing the user to feel the haptic deformation at the contact point, visual deformation of the area around the contact point is computed on the GPU.

One of the limitations of the algorithm is the simple Euclidean distance used to define the amount of deformation at a particular vertex and fragment. The algorithm presents some undesired side effects when deforming areas close to the contact point (in a straight line) but disconnected from the affected area. A better approach would be to compute the geodesic distance. Unfortunately, the geodesic distance cannot be easily computed on the GPU because it lacks global information about the object topology.

However, the deformation achieved by the algorithm has shown to be realistic for most parts of the models used in the ventriculostomy simulator.

The algorithm considers a single contact point. However, the same approach could be easily extended to multiple-point haptic applications using an object-to-object collision detection library.

Since collision detection and computation of forces are performed with the original (undeformed) geometry, this approach cannot be extended to plastic (i.e. permanent) deformation.

Beyond the limitations mentioned above, the algorithm has shown to be robust enough to simulate soft tissue deformation without affecting the graphics and haptics rendering performance. Even though the algorithm has been designed with the ventriculostomy simulator in mind, it could be extended to other more general surgical simulators, for instance liver biopsy or percutaneous spinal puncture. Even non-medical applications can benefit from this GPU-based approach. For example, Yoganandan et al. (2009 and 2010) implemented a haptics-based simulator for prototyping flexible touch screen mobile devices on the *ImmersiveTouch*®, using this algorithm.

8. VALIDATION OF THE VENTRICULOSTOMY SIMULATOR

8.1 Introduction

A series of experiments were performed in order to validate the ventriculostomy simulator on the *ImmersiveTouch*®. Real CT DICOM data sets of patients at the University of Illinois Medical Center were used to generate the virtual 3D models, in the entire spectrum between normal and extremely complex cases. Three of these validation experiments were conducted at the Annual Meeting of the American Association of Neurological Surgeons (AANS) in three consecutive years (Figure 53). The final experiment is currently being conducted at the Dr. Allan L. and Mary L. Graham Clinical Performance Center at UIC in collaboration with the Departments of Neurosurgery at Rush University, Northwestern University, University of Chicago, and the University of Illinois at Chicago.

8.2 Experiment conducted at AANS 2006 with normal ventricles

At the 2006 Annual Meeting of the AANS in San Francisco, CA, the Young Neurosurgeons Committee organized a surgical competition (called "Top Gun") for residents and fellows using three different emerging simulators. Ventriculostomy was one of the procedures tested and its results are reported here. The performance of 78 participants was evaluated for success rate and accuracy of coronal ventriculostomy catheter placement using our ventriculostomy simulator and a virtual head derived from a CT scan of a real patient with normal ventricular anatomy. Participants consisted of 60 residents and 18 fellows selected by the Young Neurosurgeons' Committee through an open solicitation. Accuracy of simulated ventriculostomy catheter placement was evaluated comparing the position of the tip of the catheter and the ideal target, which is the foramen of Monro. Cannulation of the ventricular system by the tip of the virtual catheter was considered a successful attempt. If the tip of the virtual catheter ended up outside of the ventricles, even if it was plausible that one of the openings of the catheter was in the ventricles, the attempt was considered failed (Banerjee et al., 2007).

Figure 53. *ImmersiveTouch*® ventriculostomy simulator at AANS.

The data consists of a one-time performance (single trial) of each participant inserting the catheter, following a detailed explanation during a period in which they were permitted to observe other individuals' performances and to ask detailed questions.

The haptic and graphic materials of the 3D models rendered by the simulator were fine-tuned by faculty members and senior residents at UIC's Department of Neurosurgery before the device was used at AANS.

Four pre-drilled burr-holes were presented (labeled North, South, East and West) (Figure 54). The West burr hole, located exactly at the Kocher's point, is the correct choice for performing ventriculostomy on this patient considering a normal ventricular anatomy.

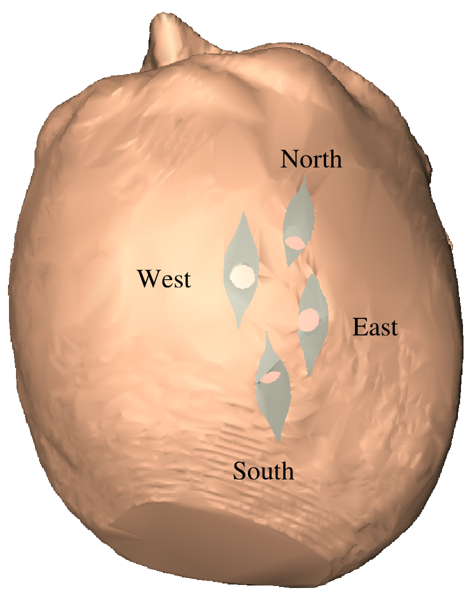


Figure 54. Virtual patient's head showing the four pre-drilled burr holes.

8.2.1 Results

The participants were requested to choose one of the four pre-drilled burr holes before performing the ventriculostomy. Most of them (53) correctly identified the appropriate burr hole located at the Kocher's point (Table III and Figure 55).

TABLE III

SELECTION OF BURR HOLES

Pre-drilled burr holes	Number of occurrences
West (correct burr hole at Kocher's point)	53
East	11
North	1
South	13

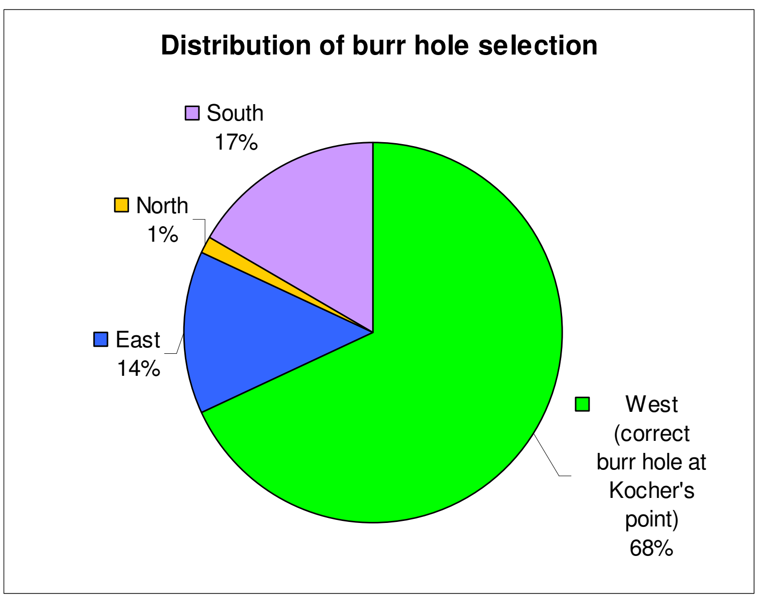


Figure 55. Distribution of burr hole selection.

Table IV shows the mean, standard deviation, minimum and maximum distance from the tip of the catheter to both the foramen of Monro and the burr hole obtained by the experiment.

TABLE IV

RESULTS OF STUDY AT AANS (NORMAL VENTRICLES)

Parameter	**Error to ideal target (FOM)**	**Catheter depth (from skull)**
Mean	16.09	63.63
Standard deviation	7.85	13.45
Min	2.68	30.00
Max	49.62	120.00

Out of 78 catheter insertions, 21 attempts were unsuccessful to cannulate the ventricles, and the remaining attempts ended up in different anatomical areas of the ventricular system, where only 45 were correctly placed in the ipsilateral lateral ventricle, as shown in Table V.

Results from this experiment using the *ImmersiveTouch*® are useful to address an important challenge in validation of ventriculostomy simulation through comparison with clinical data. The retrospective evaluation of the head CT scan of 97 patients who underwent 98 free-hand ventriculostomy placements at the University of Missouri in Columbia (Huyette et al., 2008), can be utilized to validate the ventriculostomy simulator. This makes the task of comparison with clinical data quite meaningful.

TABLE V

DISTRIBUTION OF CATHETER PLACEMENT

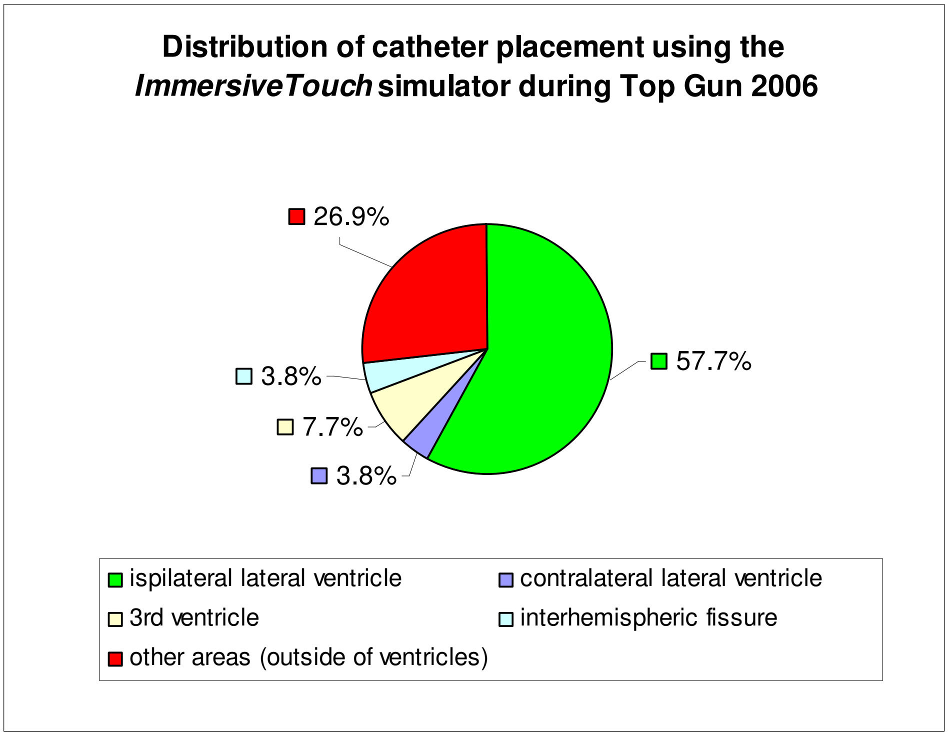
Final catheter position	Number of attempts
Ispilateral lateral ventricle	45
Contralateral lateral ventricle	3
Third ventricle	6
Inter-hemispheric fissure	3
Outside of ventricles	21

At the outset it is recognized that because the ventriculostomy simulation is a part-task, a direct comparison with the clinical procedure is not very meaningful. Instead, we report an indirect comparison utilizing the primary strength of the simulation approach and the primary strength of the clinical approach, namely the ease of repeating the same simulated ventriculostomy procedure for multiple participants, thereby controlling experiment variability in the simulation approach and the ease of retrospectively examining multiple clinical ventriculostomy cases and enhancing realism through clinical approach.

As discussed in section 3.4, the retrospective evaluation performed at the University of Missouri found that the accuracy error to the foramen of Monro was 16.1 ± 9.6 mm. The similarity of the values obtained for mean error of about 16 mm and standard deviation of approximately 8 to 9 mm in both experiments is a significant observation.

Moreover, a comparison of the distributions of the catheter placement found by the simulator experiment at AANS versus those found by the retrospective assessment with real patients indicates a very strong scientific evidence of the high level of similarities between both results (Figure 56). Both studies have given very close percentages for ipsilateral cannulations (57.7% vs. 56.1%), failed cannulations (26.9% vs. 22.4%), and placements inside of the 3rd ventricles (7.7% vs. 8.2%).

Finally, with respect to reaching the ventricle, there was no significant difference between the success rate observed in our study using the simulator (73%) and the success rate in the clinical setting as reported by Huyette et al. (2008) (79%). It should be noted that the simulator results are based on the performance of participants drawn from a pool made up primarily of residents, whereas the clinical results were more likely to be based on the performance of practicing neurosurgeons. This might be the reason of the subtle difference in the success rates. Once again this represents an interesting initial observation on how closely a simulator can capture a real situation.



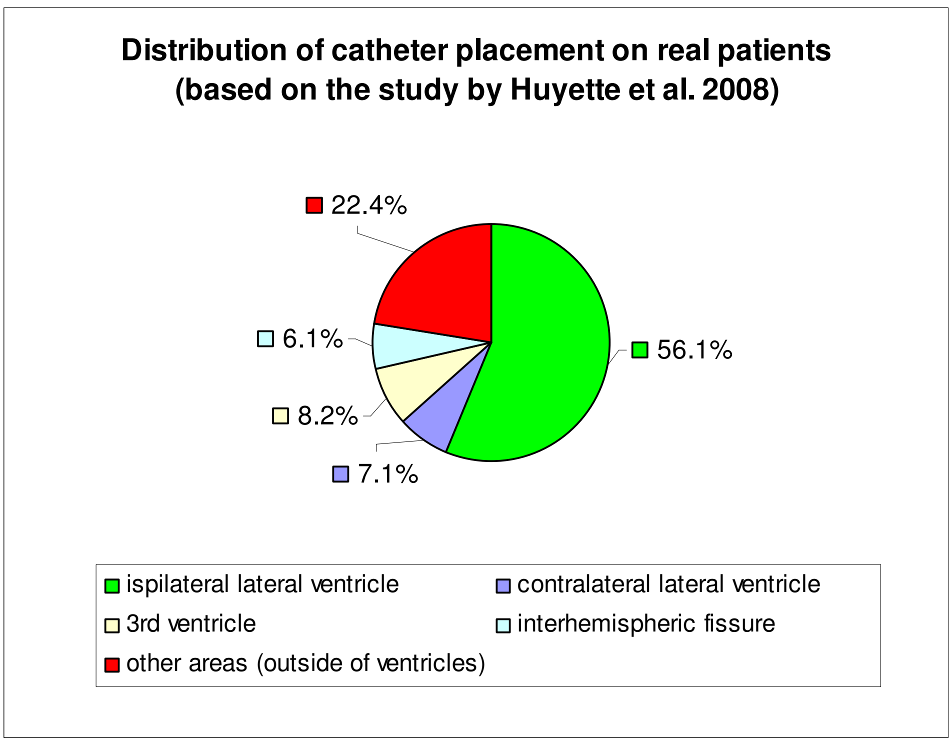


Figure 56. Comparison between experiments using simulation and with real patients.

As noted before, the 98 ventriculostomy procedures studied by Huyette et al. (2008) were performed in 97 different patients, whereas in our study the 78 participants attempted the simulated procedure in one virtual patient. The strength of the virtual reality approach is the capacity for standardization, that is, multiple participants all attempting the procedure in what amounts to a single case.

Although the part-task simulator can certainly demonstrate an individual's spatial skill in placing a catheter, it cannot be used to measure the temporal skill. Ventricular catheters are normally placed in emergency settings and because the procedure can be life-saving, time, in addition to accuracy, is essential.

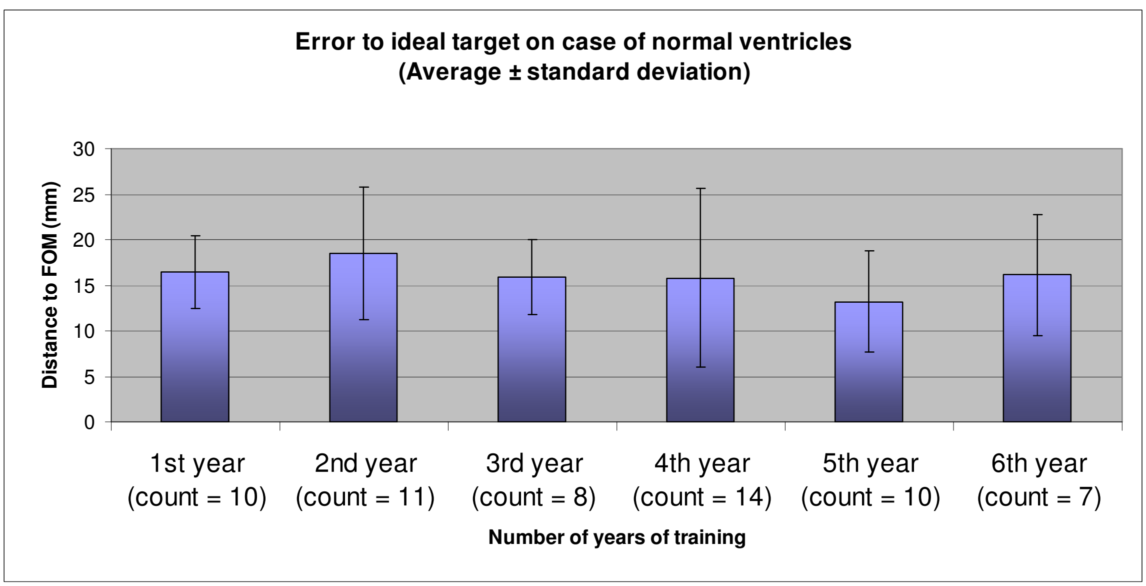


Figure 57. Accuracy of catheter insertion per level of training (normal ventricles).

Another observation obtained by the experiment is that, surprisingly, there does not seem to be a strong correlation between the level of training as measured by the number of years in residency and accuracy of the catheter insertion, as shown in Figure

57. A possible explanation is that accuracy may be determined by the actual number of procedures performed rather than the level of training. However, Figure 58 shows the success rate per level of training. Peak performance occurred in third-year residents, with the biggest jump in accuracy occurring between first-year residents (50% success on first attempt) and second-year residents (82% success on first attempt). Performance dropped off in the fifth and sixth years of training (Banerjee et al., 2007).

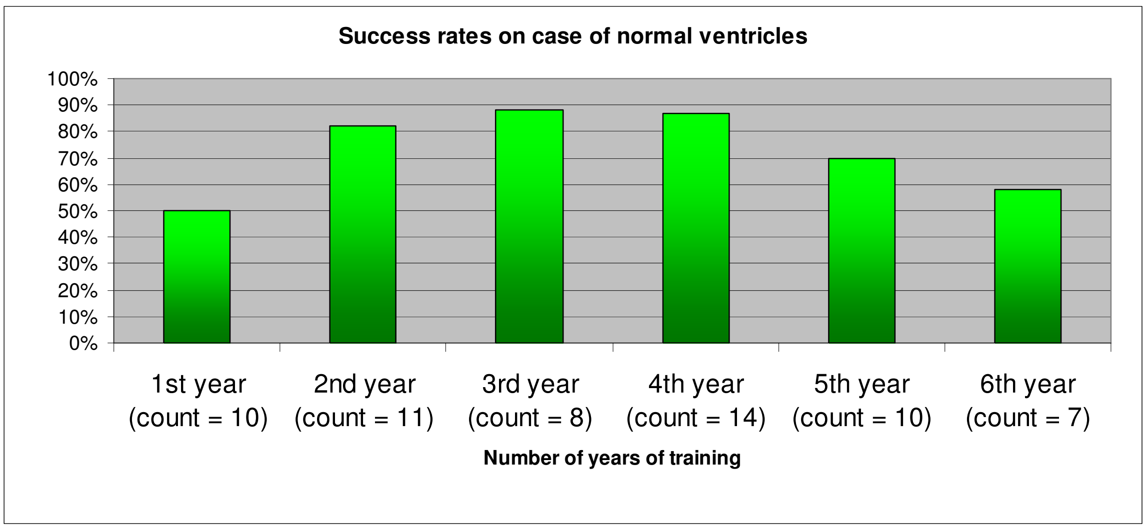


Figure 58. Success rates per level of training (normal ventricles).

The results illustrate the natural learning curve of neurosurgery residents on this procedure. Since ventriculostomy is a high volume procedure performed primarily by junior residents, they obtain sufficient experience to reach a high level of accuracy by the second year of training. The drop in accuracy in years 5 and 6 may reflect a shift to more complex surgical procedures, decreasing the volume of ventriculostomy procedures and resulting in declining proficiency due to insufficient practice. Future patient-safety-oriented studies will determine: 1) whether practice on the *ImmersiveTouch*® simulator can facilitate and accelerate the initial acquisition of skill in year one, and 2) whether continued practice using *ImmersiveTouch*® can prevent the deterioration of skills at subsequent years.

8.3 Experiment conducted at AANS 2007 with shifted ventricles

The 2007 AANS Annual Meeting Top Gun competition in Washington, DC, provided an opportunity to re-examine accuracy of virtual ventriculostomy catheter placement by 48 neurosurgical residents (Lemole et al., 2009).

Although ventriculostomy is a common neurosurgical procedure, certain pathologic entities such as brain tumors, hematomas or cerebral edema can shift the normal ventricular anatomy, greatly increasing the difficulty of cannulating the ventricle. The complexity of the simulation was increased by using a real case of a patient with distortioned ventricular morphology in response to cerebral mass effect and reassessed resident performance. Unlike the previous year event, two catheter insertion attempts were required to the participants. The objective of this experiment was to analyze how the success rates and errors are affected by the years of training of neurosurgery residents handling a more complex case.

8.3.1 Results

Figure 59 shows the success rate by level of training based upon the first and second attempts. The experiment demonstrated that, uniformly, all residents improved by the second attempt, regardless of their level of training. The data suggest that there is an initial proficiency with ‘shifted ventricle’ cannulation that is lost by midresidency, only returning by the end of training. This seems counterintuitive for a more complex ventriculostomy when our previously reported results from the 2006 AANS Top Gun exhibition suggested just the opposite. Several points need to be considered. First, the data sample (n) for the first- and second-year residents were underrepresented relative to other levels of training and the previous evaluation. Excluding these points suggests a trend of overall improvement for both the first and second attempts as training progresses. Second, the Euclidean distances measured to the foramen of Monro (Figure 60) do not show the same loss of proficiency in the middle years of training as indicated by the low success rates in Figure 59. However, while distance to target does not measure successful cannulation, it does imply a certain understanding of the 'shifted ventricle' anatomy.

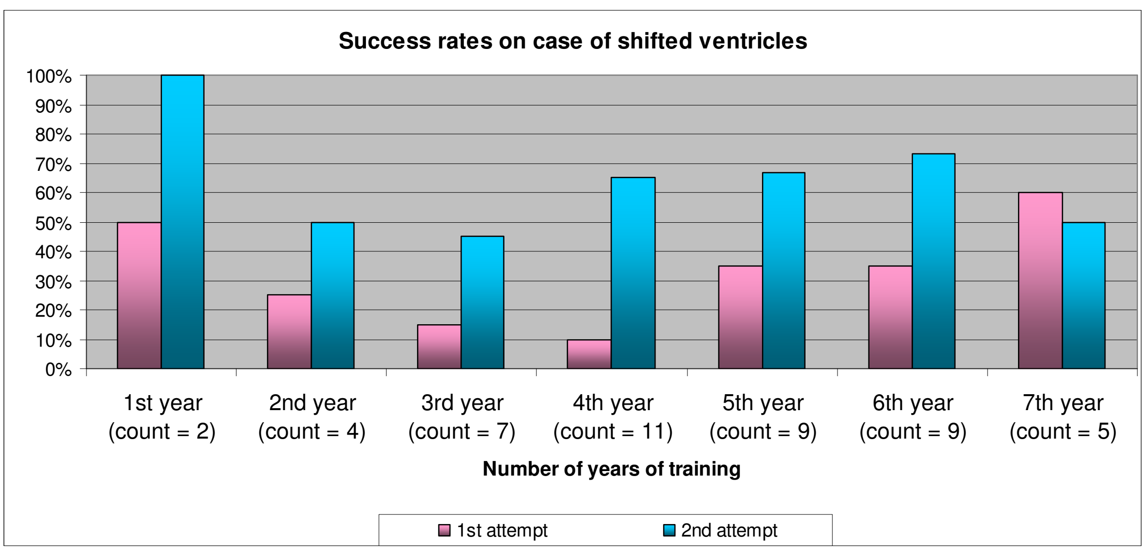


Figure 59. Success rates per level of training (shifted ventricles).

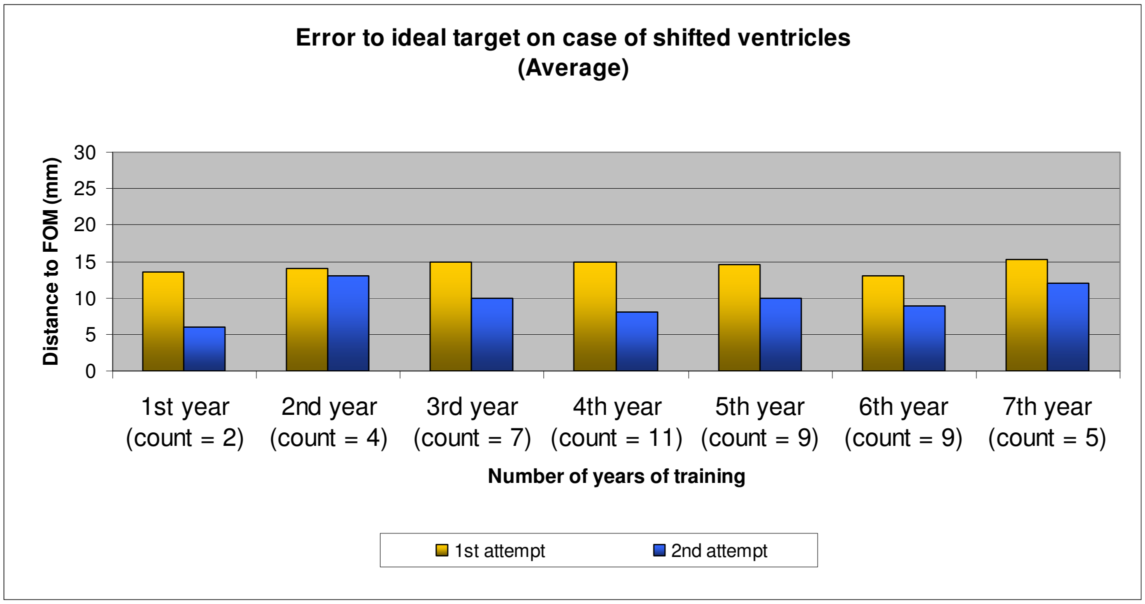


Figure 60. Accuracy of catheter insertion per level of training (shifted ventricles).

8.4 Experiment conducted at AANS 2008 with hydrocephalic brain

Ventriculoperitoneal shunt (VPS) is a common neurosurgical procedure used for the treatment of hydrocephalus. Like ventriculostomy, VPS requires the insertion of a catheter to cannulate the ventricles. However, in this case, the catheter is left in place for a long time, or even permanently, to continuously drain spinal fluid from the ventricles.

In the VPS procedure, access to the cerebral ventricle is possible through many approaches, the three most common being coronal, occipital, and parietal. The choice of which approach to use for ventricular catheterization is most often based on surgeon preference as there are no studies comparing these approaches. Regardless of the approach, most VPS procedures are performed with a free-hand method using surface landmarks.

For the 2008 AANS Annual Meeting Top Gun competition held in Chicago, IL, the ventriculostomy simulator was adapted to simulate a part task VPS procedure by adding all three common techniques for cannulation of the lateral ventricle from both right and left sided approaches (Oh et al., 2009). Each resident/fellow was given standard instructions and attempted 6 ventricle cannulations (right coronal, right parietal, right occipital, left coronal, left parietal, and left occipital) as shown in Figure 61.

Seventy residents and fellows attempted 420 catheter insertions in a part-task VPS simulation. CT scans showing the ideal target for each technique were shown to each participant prior to their practice in the simulator. In addition, some participants were shown didactic slides that provided information on standard landmarks and trajectories for each of the three techniques to study if this would affect accuracy and success rates (Figure 62).

Chi-square, one-way ANOVA and Student's T test were used for statistical analysis of difference significance of the performance results obtained from both groups (with and without the prior didactic presentation).

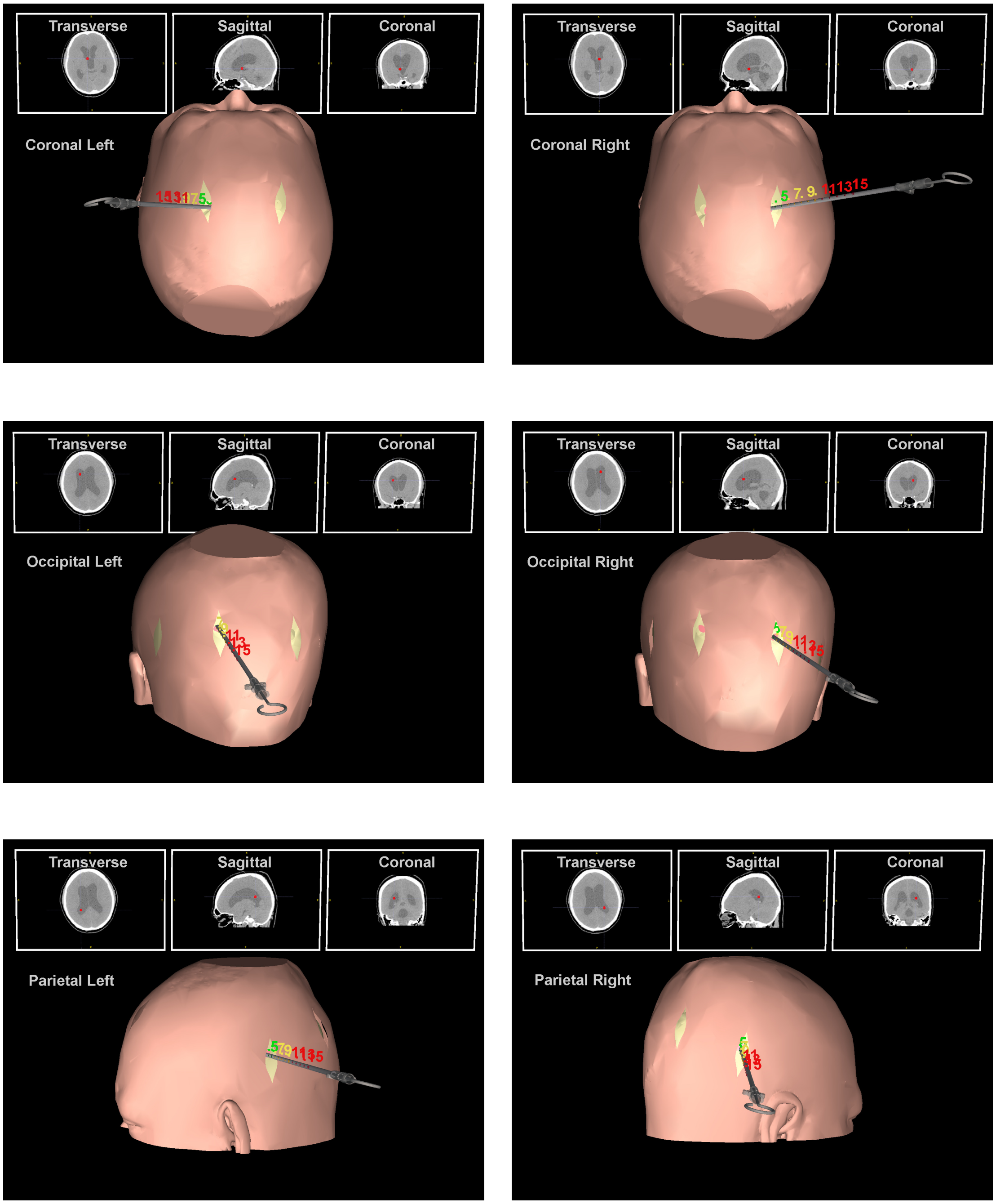
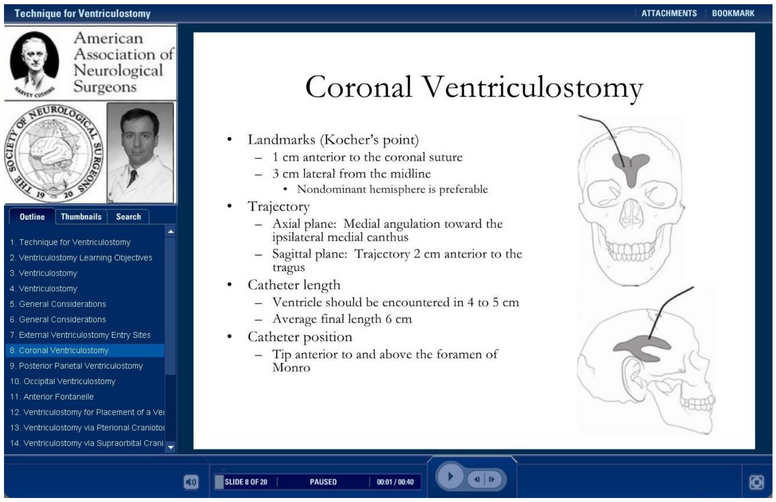
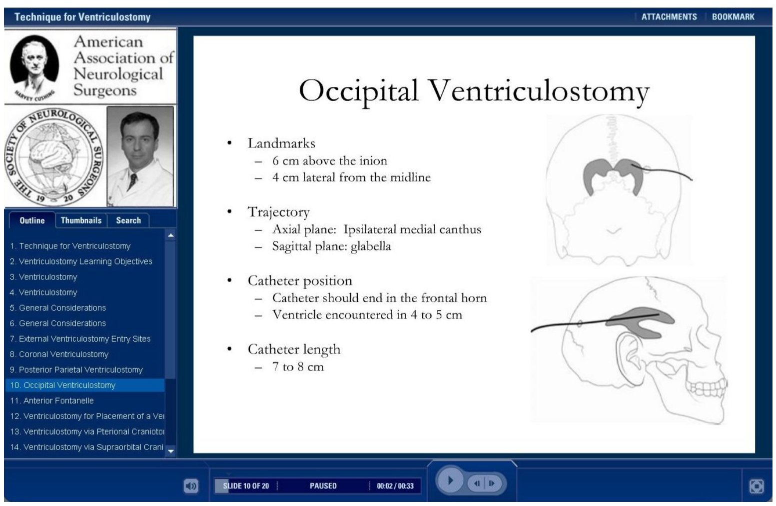


Figure 61. Multiple approaches for VPS placement.





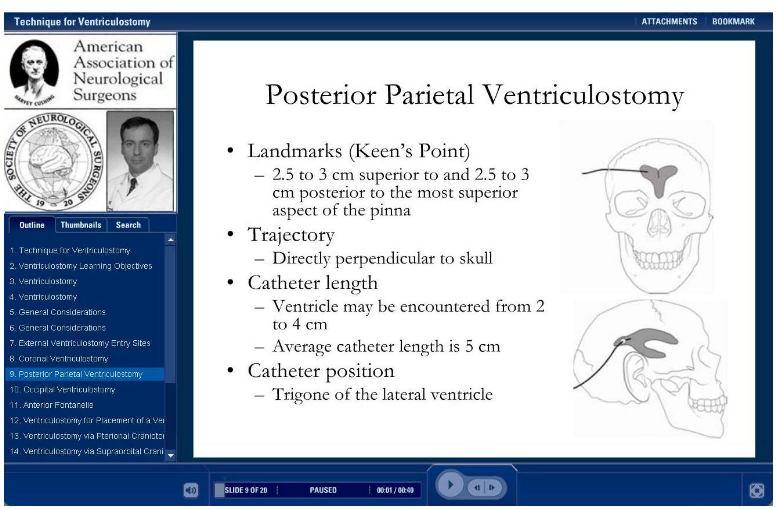


Figure 62. Didactic slices. (Image courtesy of Dr. Vincent Traynelis, MD)

8.4.1 <u>Results</u>

The goal of this study was to answer the following questions:

1. Does the fact of viewing a didactic presentation on ventriculostomy immediately prior to the simulation improve accuracy and successful cannulation of the ventricles?
2. Is there any technique (coronal, occipital, and parietal approaches) that demonstrated better success rates?
3. Does it make a difference whether a right or left sided approach is taken?

Regarding the first question, the experiment showed that among participants watching the presentation, 59 failed and 139 succeeded in cannulating the target ventricle. In contrast, among participants who did not view the presentation, 74 failed and 148 succeeded. Figure 63 shows that there was no significant difference between these two groups (p=0.437), and suggests that this type of didactic instruction does not convey any advantage in terms of successful ventricular cannulation in this simulation.

When comparing the accuracy of ventricular catheter placement between those who viewed the slides and those who didn't, the study found again that there was no significant difference (20.81±11.45 versus 20.95±10.10, respectively), as shown in Figure 64. Similarly, if we subdivide the results by technique, coronal vs. occipital vs. parietal approaches, there are no significant differences between these two groups.

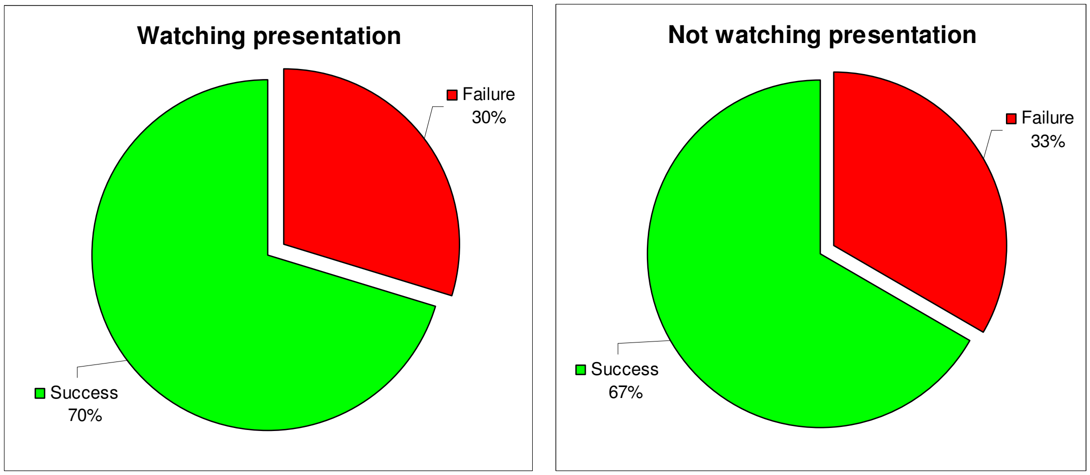


Figure 63. Difference of success rates between the groups.

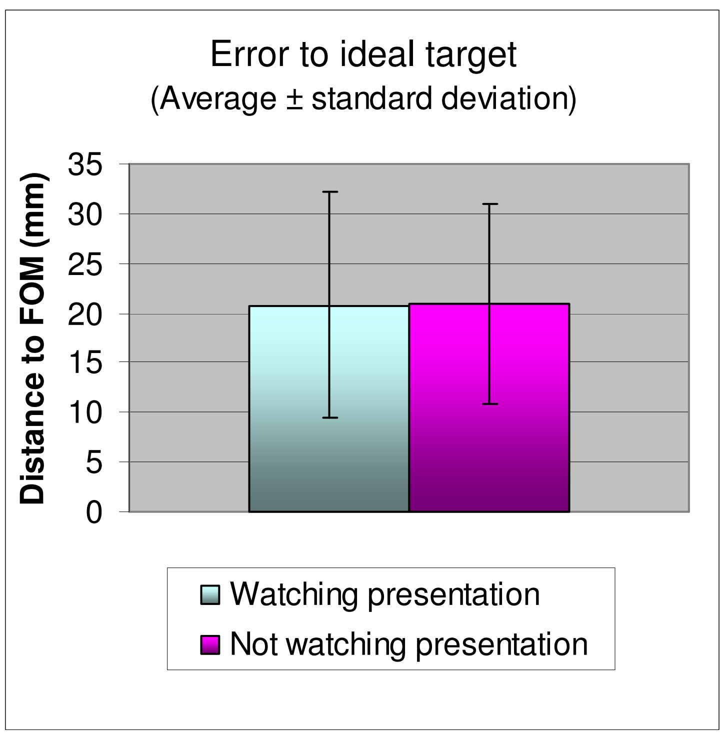


Figure 64. Accuracy of catheter insertion per group.

Respect to the second question, a comparison between coronal, occipital, and parietal approaches shows that the coronal technique for ventricular access was associated with a higher rate of successful cannulation of the ventricle than either of the other techniques (Table VI). This difference was statistically significant ($p<0.001$) and supports the use of coronal approach for VPS if using only surface landmarks (Figure 65).

TABLE VI

DISTRIBUTION OF FAILURE AND SUCCESS PER APPROACH

Approach	**Number of failure**	**Number of success**
Right coronal	11	59
Left coronal	9	61
Right occipital	25	45
Left occipital	24	46
Right parietal	30	40
Left parietal	34	36

For participants who successfully cannulated the ventricle, we compared the accuracy among the three different techniques. The mean error to the ideal target within the ventricle (in mm) of the parietal approach was 16.41 ± 8.37. The mean error of the occipital approach was 23.64 ± 14.17, and with the coronal approach it was 21.59 ± 7.95. ANOVA comparison shows that this is a significant difference ($p<0.001$) and suggests that if accuracy within the ventricle is the primary goal in VPS procedures, the parietal technique may be preferred (Figure 66).

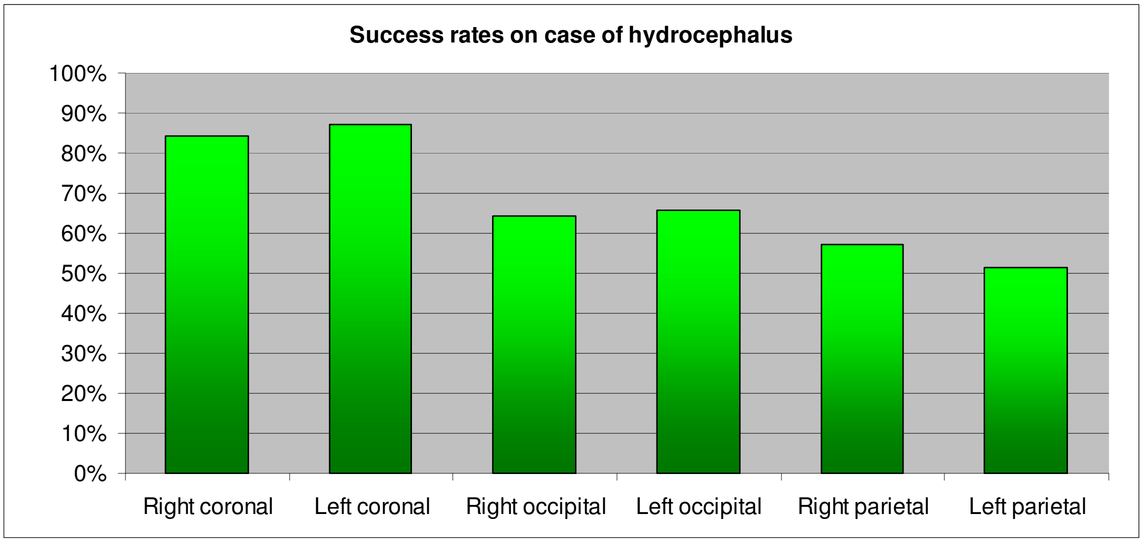


Figure 65. Success rates per approach.

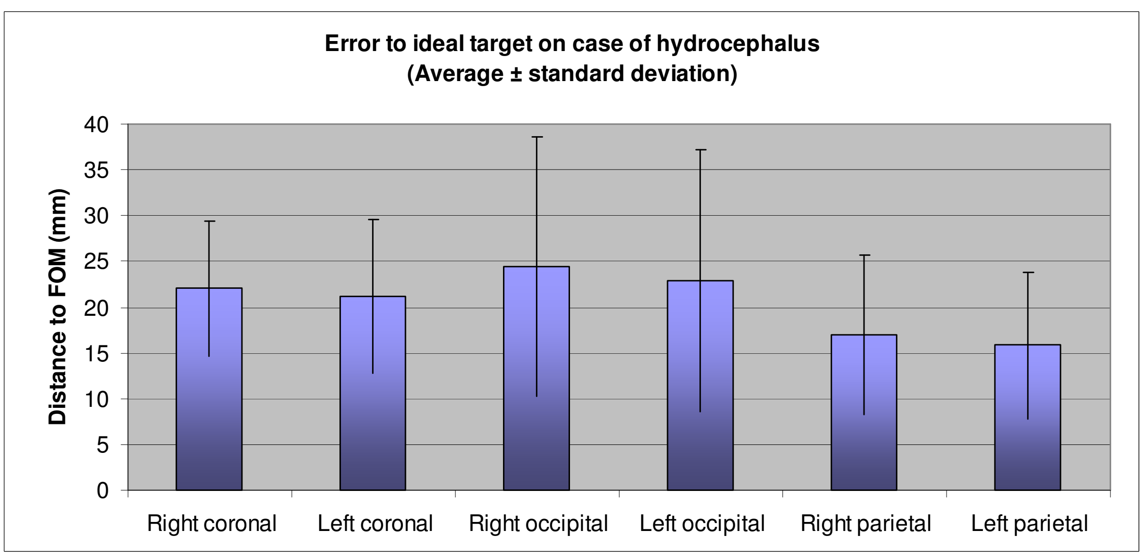


Figure 66. Accuracy of catheter insertion per approach.

Finally, there was no difference between right and left sided approaches when looking at rates of successful cannulation of the ventricles (p=0.916). If left and right approaches are subdivided into coronal, occipital and parietal techniques, statistical differences are not found (Table VII).

TABLE VII

ACCURACY DIFFERENCES BETWEEN LEFT AND RIGHT SIDES

Approach	Right	Left	P-value
Overall	21.36±10.65	20.41±10.88	0.457
Coronal	22.04±7.42	21.16±8.46	0.543
Occipital	24.39±14.18	22.91±14.29	0.624
Parietal	16.94±8.73	15.80±8.02	0.558

8.5 <u>Experiment conducted at UIC's Clinical Performance Center</u>

At the time of this writing, a more exhaustive experiment is being conducted at the Dr. Allan L. and Mary L. Graham Clinical Performance Center (CPC) at UIC, by Professors Rachel Yodkoswky and Allan Schwartz, from the Department of Medical Education, and Professor Ali Alaraj, from the Department of Neurosurgery at UIC. The main goal is to obtain qualitative user's feedback on their experience using the simulator and evaluate their performance during a long practice session of about 2.5 hours. The experiment consists of performing ventriculostomy on a library of 15 different patients with normal, hydrocephalic, shifted and slit ventricles (Figure 67).

Normal and hydrocephalic | Shifted | Slit

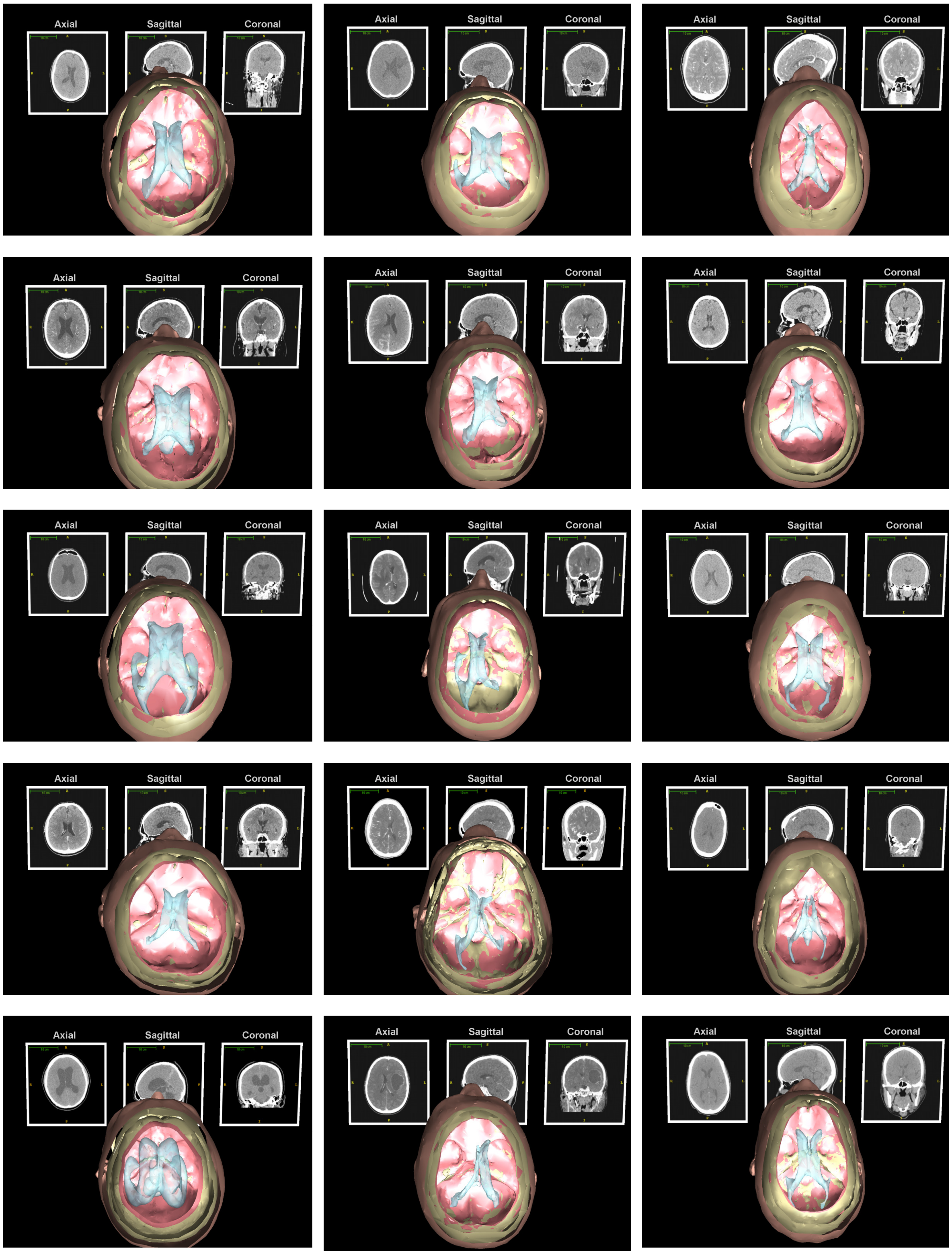


Figure 67. Library of 15 different cases.

Fifteen Neurosurgery residents from the University of Illinois Medical Center, Rush University Medical Center, Northwestern Memorial Hospital, and University of Chicago Medical Center are voluntarily participating in this experiment. The purpose of this study is to evaluate the effects of practice on the simulator and how this would improve the performance in terms of success rates and catheter placement accuracy on cannulating ventricles on real patients.

The study is organized in two sessions: practice and follow up. The practice session consists of four phases: orientation, pre-practice test, practice trials, and post-practice test. Table VIII shows an example of one of the protocols followed in the experiment.

TABLE VIII

EXAMPLE OF PROTOCOL USED FOR THE EXPERIMENT

Phase	Order	Brain	Ventricle type
Orientation	0	E	Hydrocephalic
Pre-test	1	B	Normal
	2	F	Shifted
	3	L	Slit
Practice	1	E	Hydrocephalic
	2	J	Shifted
	3	C	Normal
	4	M	Slit
	5	F	Shifted
	6	B	Normal
	7	H	Shifted
	8	O	Slit
	9	A	Normal
	10	L	Slit
	11	I	Shifted
	12	K	Slit
Post-test	1	D	Normal
	2	G	Shifted
	3	N	Slit

The orientation phase is performed employing the 3D data set obtained from the patient with hydrocephalous used by the VPS experiment. During the orientation, the participants are instructed on the use of the simulator and they are allowed to cannulate the ventricles multiple times, inspecting the final catheter position inside of the brain with the use of the cutting plane tool. The orientation practice continues until the resident is comfortable with the simulator for a period of no more than 10 minutes.

During the pre-test phase, the participants are requested to make three attempts for each of the three given cases (normal, shifted and slit), even when the first or second attempts were successful. In this phase the participants are not allowed to use the cutting plane tool.

Next in the practice phase, the participants are presented with 12 cases with different levels of complexity based on the brain anatomy. Participants must practice for no more than 10 minutes in each case, inserting the catheter and exploring the anatomy with the cutting plane tool after each insertion, for a total time of 2.5 hours.

Finally, during the post-test phase, the participants are requested to make three attempts for each of the three last cases, without using the cut-away tool.

The complete original CT scan data of all 15 cases are available to the participants so they can study the patient's anatomy, analyze the complexity of the case, and estimate the orientation and depth of the catheter. The participants are allowed to navigate among all CT slices using an external application at any time during the experiment.

In the days following the practice session, the residents must document their ventriculostomy procedures on live patients for a period of one month and return to the simulator for a follow-up session cannulating the ventricles on the same three cases used for their pre-test. They must continue documenting their live procedures for another month.

In addition to the performance measurement given by the ventriculostomy simulator, the experiment also involves a survey on the user's experience after both sessions (Table IX and Table X).

TABLE IX

FEEDBACK QUESTIONNAIRE AFTER PRACTICE SESSION

How realistic was the virtual image?
How realistic was the sensation when puncturing the ventricle?
How helpful was it to view the CT scan?
Ability to use the CT scan to aid in estimating the location of the ventricle
Ability to aim the probe towards the ventricle
Ability to sense the pressure change when entering the ventricle
Ability to estimate how far the catheter should be advanced within the ventricle
Overall ability to perform a ventriculostomy on a live patient
Overall, how satisfied were you with this practice session

TABLE X

FEEDBACK QUESTIONNAIRE AFTER FOLLOW-UP SESSION

Ability to use the CT scan to aid in estimating the location of the ventricle
Ability to aim the probe towards the ventricle
Ability to sense the pressure change when entering the ventricle
Ability to estimate how far the catheter should be advanced within the ventricle
Overall ability to perform a ventriculostomy on a live patient
How useful would this practice be for a new resident prior to performing live EVDs?

8.5.1 Preliminary results

Figure 68 shows the results of the questionnaire after the practice session, indicating the average and standard deviation, as well as the distribution percentages. The survey questions were answered in a 1-to-5 scale as follows:

TABLE XI

ANSWERS TO THE FEEDBACK QUESTIONNAIRE

Value	Corresponds to:
1	Not at all
2	Somewhat
3	Much
4	Very much
5	Extremely

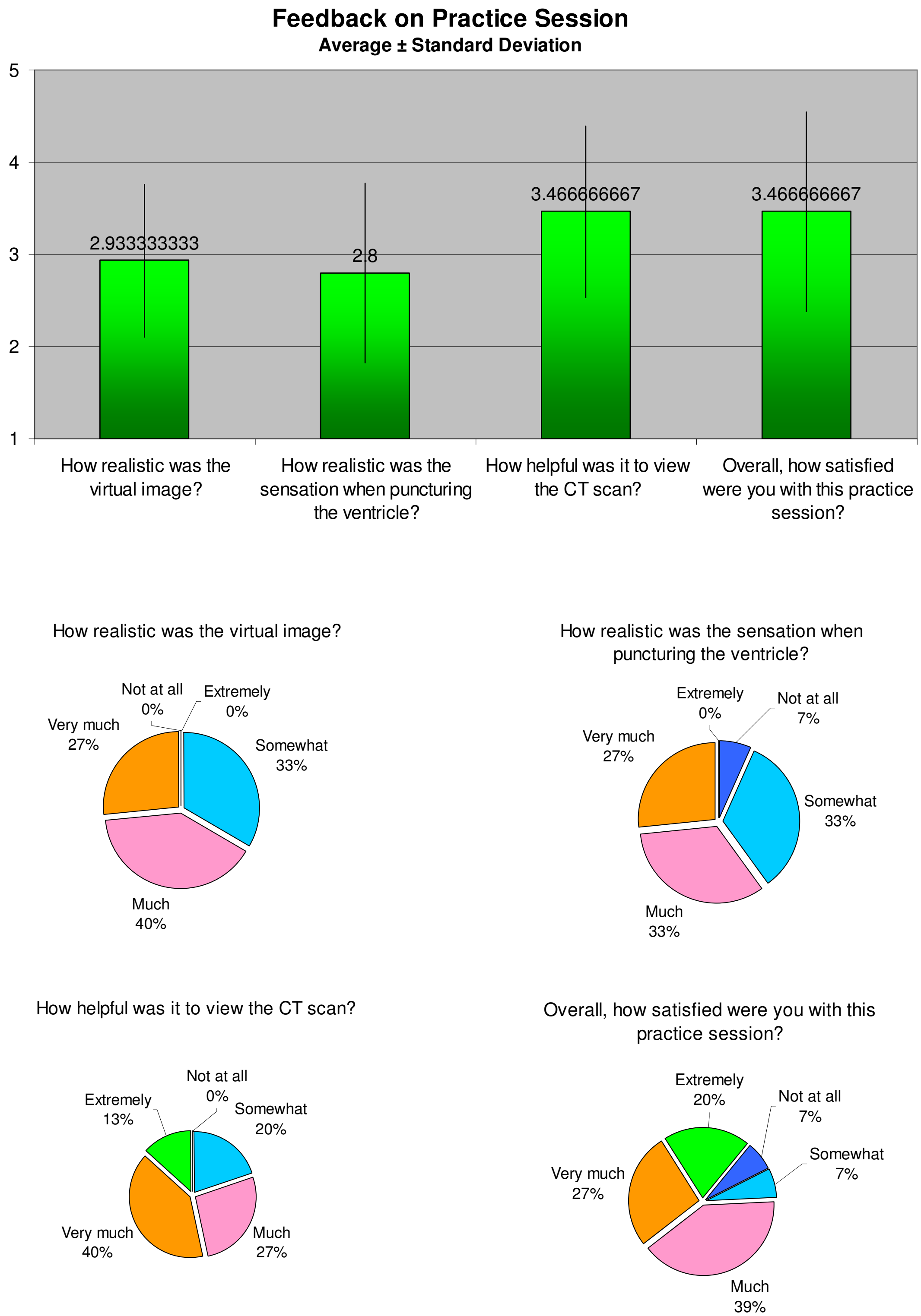
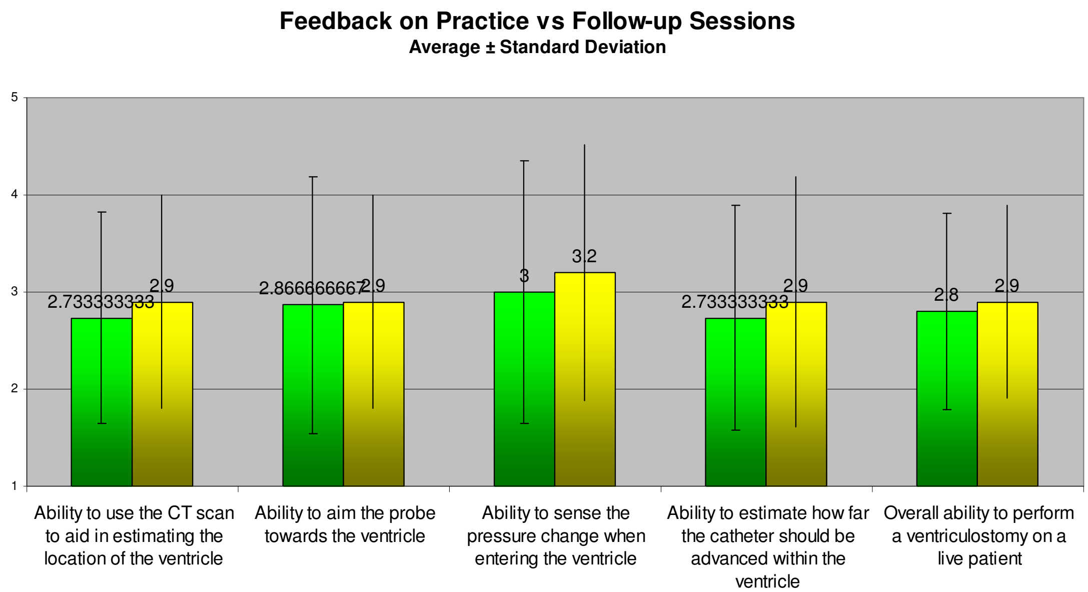


Figure 68. Feedback after practice session.

Figure 69, Figure 70 and Figure 71 show the comparison between the feedback obtained after the practice session versus the feedback after the follow-up session. Figure 72 gives the results of the survey after the follow-up session.



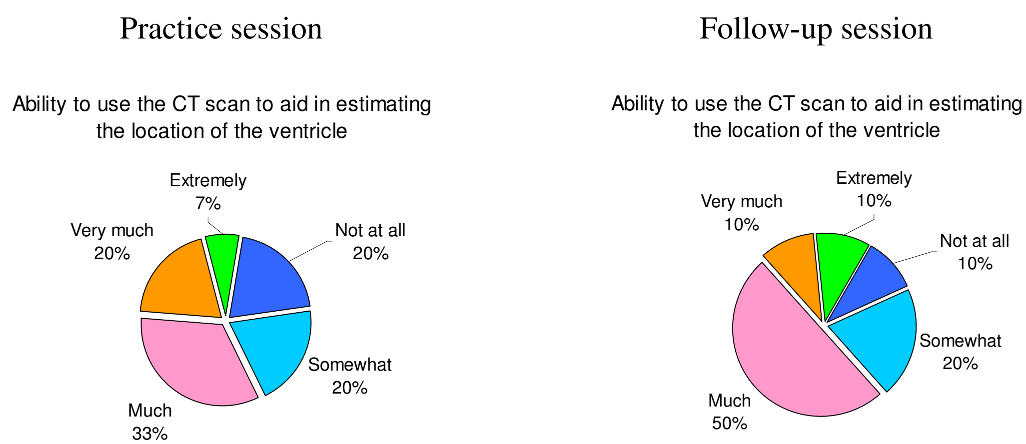


Figure 69. Comparison between the feedback after practice and follow-up sessions.

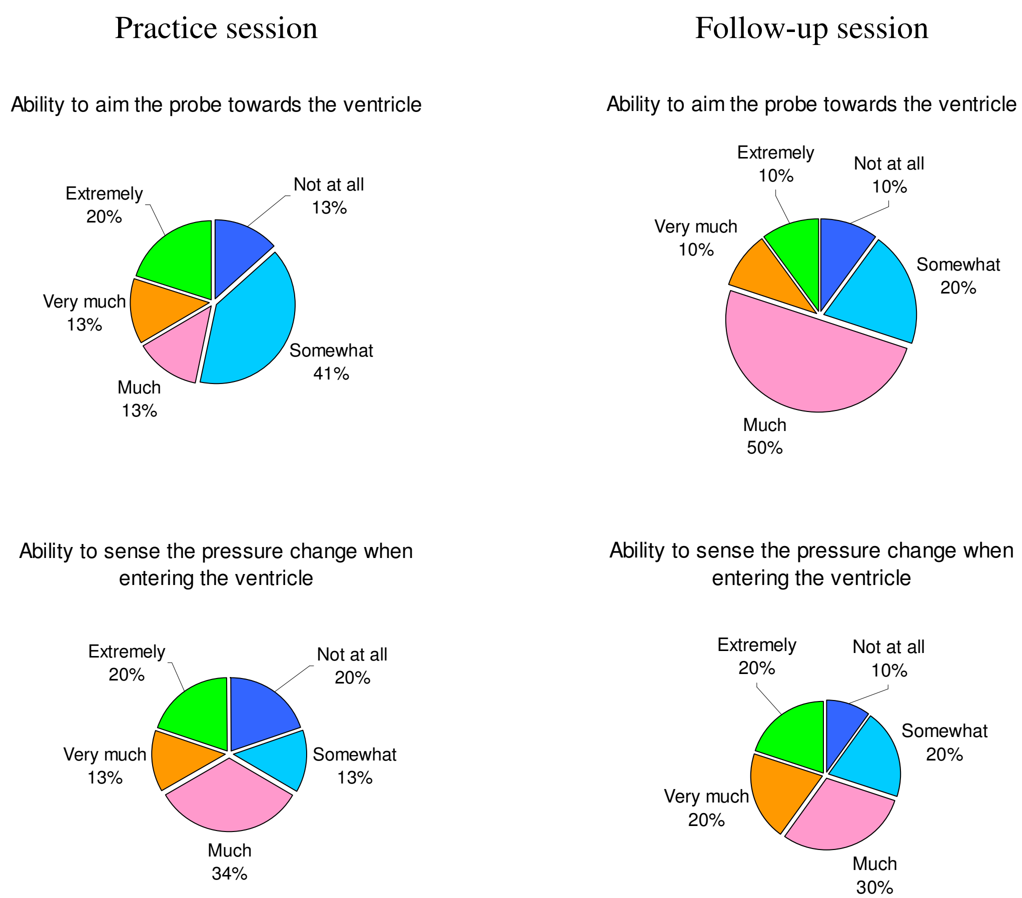


Figure 70. Comparison between the feedback after practice and follow-up sessions (cont.).

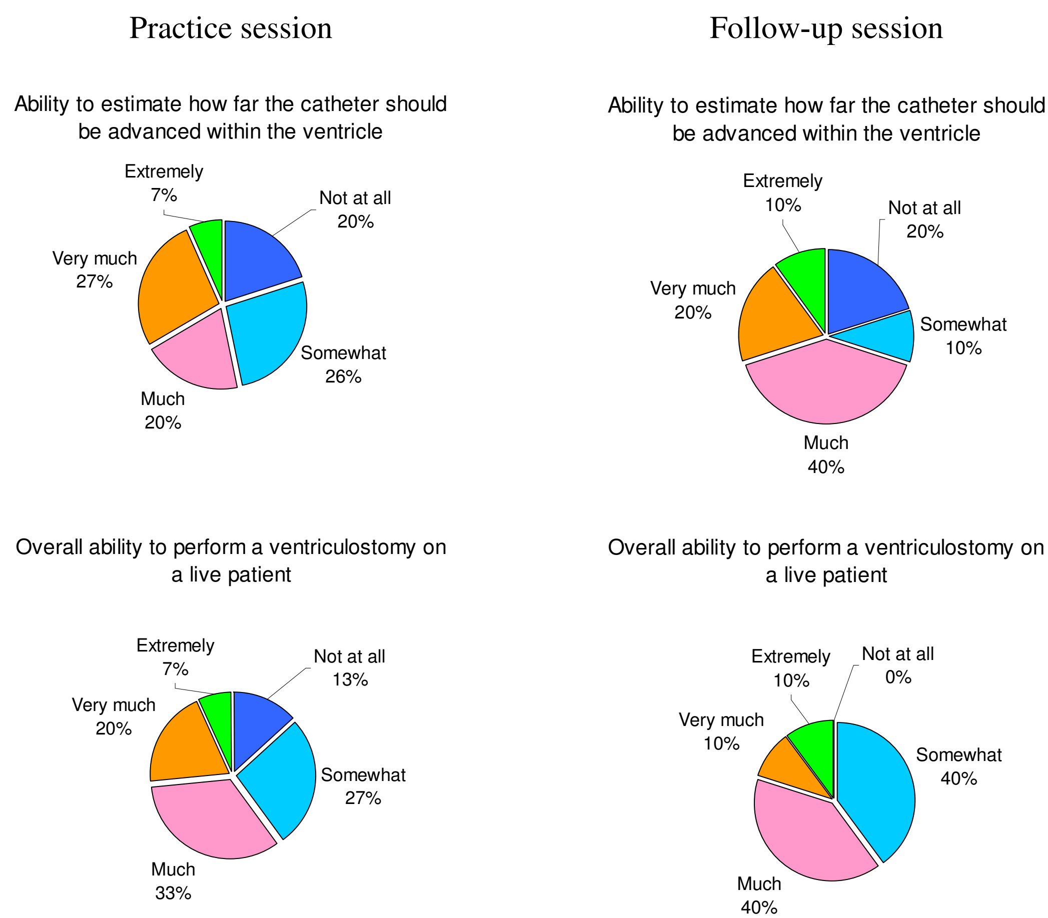


Figure 71. Comparison between the feedback after practice and follow-up sessions (cont.).

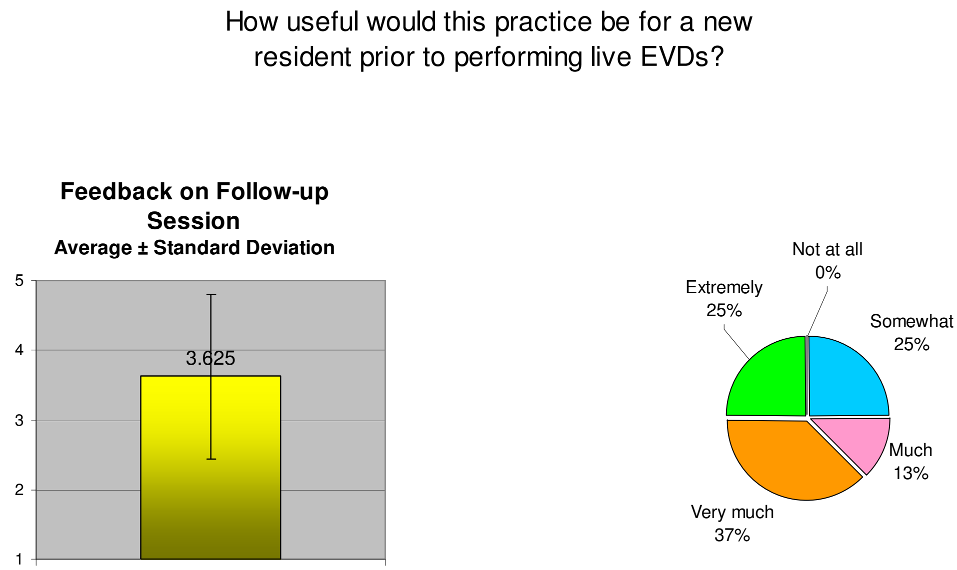


Figure 72. Feedback after follow-up session.

Figure 73 shows the average and standard deviation of the overall performance based on the error to the ideal target (FOM). Note that, as expected, there is an improvement between the pre-test and the post-test sessions, product of the learning process enhanced by the simulator. The preliminary results do not indicate an improvement on the accuracy of the catheter insertion after the follow-up session carried out one month after the practice on the simulator. This may suggest that continued practice on the simulator might be needed to improve learning retention with time.

An exhaustive evaluation of all ventriculostomies performed by the 15 participants of this study on real patients, during the monthly period between the practice and follow-up sessions, is currently being conducted by the Department of Neurosurgery at UIC. Once completed, this evaluation will be able to give a better indication of how much practice on the ventriculostomy simulator affects accuracy of catheter insertion and success rates on real patients.

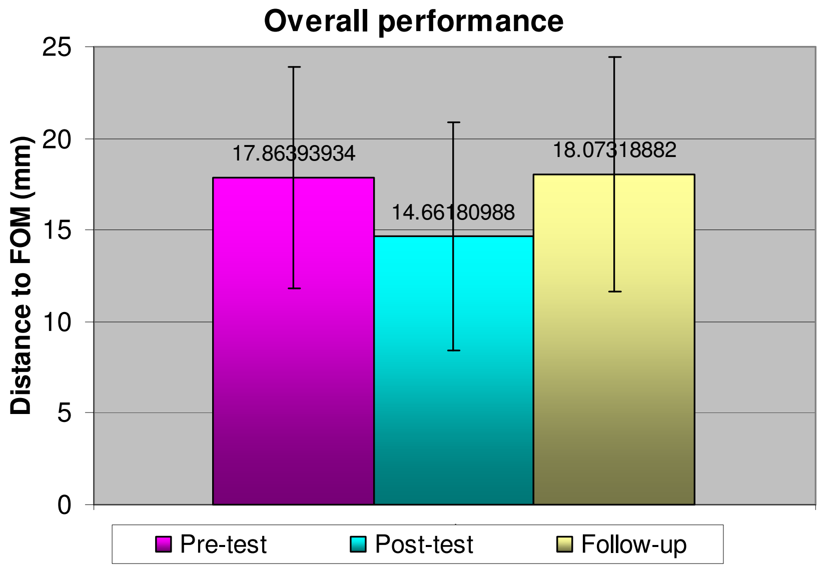


Figure 73. Overall performance.

8.6 Chapter conclusions

The experiment conducted in 2006 shows that the simulator accurately reproduces the part-task experience of cannulating the ventricle with a virtual ventricular catheter. Given the importance of neurosurgical simulation for training and recertification, this simulator represents a step forward. The results from testing with 78 neurosurgical residents and fellows seem to replicate some results (such as the distribution of catheter placement, as well as mean and standard deviation for distance between the final position of the catheter tip and the foramen of Monro) from a previously reported clinical study based on 98 procedures performed in an ICU setting. Hence, this analysis lays a strong foundation to support the validation of the ventriculostomy simulator to be able to reproduce real conditions comparable to ventriculostomy performed in the OR. This allows us to use the simulator not only as a valuable training tool, but also as a "what-if" tool for pre-surgical planning to describe what would happen in a real scenario without any undesired consequences to real patients.

The study performed in 2007 suggests that, as expected, successful first attempts to cannulate the virtual ‘shifted ventricle’ are much less frequent than previous assessments with normal virtual ventricular anatomy. Also, in terms of training effectivity, the significant improvement by the second catheter insertion attempt implies that the learning curve has been affected and the process ‘jump-started’.

Furthermore, the study performed in 2008 has demonstrated that some approaches for VPS placements are more favorable to obtain higher success rates, while other approaches facilitate more accurate results. The experiment also showed that left and right approaches are statistically indifferent in terms of success rates and placement accuracy. In addition, the study has shown that traditional (non-interactive) ways to train neurosurgeons using text books and 2D diagrams do not help to improve their performance, highlighting the importance of more interactive 3D simulation in surgical education.

Finally, the experiment being conducted at UIC’s CPC shows that the simulator delivers an acceptable realistic scenario in terms of both graphics and haptics feedback. The level of realism is high enough to produce a satisfactory practice session, which motivates residents to learn by a trial-and-error approach. This is something that would be too risky, or even impossible, to perform on real patients. The ability to feel the “pop” once the ventricles are cannulated and to cut away the virtual patient’s head to visualize the catheter once it is inserted, have been some of the most valuable assets according to the participants in this study. Comparing the follow-up and practice session feedback shows that the residents’ ability to interpret the CT scan data to estimate the location of the ventricles and the correct depth of the catheter, as well as to aim the catheter towards the ideal target, increase after the follow-up. Additionally, most participants agree that the practice on the simulator would be very useful for new residents to become familiar with the ventriculostomy procedure before performing on live patients.

9. FINAL CONCLUSIONS AND FUTURE RESEARCH

ImmersiveTouch®, a second-generation high-fidelity virtual reality simulator, has been introduced, being the first system that creates an augmented reality environment combining high-resolution stereoscopic visualization, viewer-centered-perspective graphics rendering, realistic haptic feedback, and perfect virtual/real-world object collocation, to successfully simulate open surgical procedures.

The limitations of previous Augmented Reality devices (poor visual acuity, lack of user's head tracking, improper graphics/haptics collocation, distracting images in the user's FOV, and inability to read text during the development phase) have motivated the design of a novel system that provides both a very useful software development platform and a faithful real-time simulation system.

The haptics-based ventriculostomy simulator developed on the *ImmersiveTouch*® allows a neurosurgical resident to locate anatomical landmarks that help to define the ideal catheter trajectory, simply by moving his or her head from one side of the virtual patient to the other, in the same way he or she would do in the OR. By manipulating a virtual catheter, perfectly collocated with a haptic stylus, the resident can perform the ventriculostomy on a virtual 3D model of a real patient, and feel the viscosity of the brain along with the distinct lack of resistance characteristic of the ventricular cannulation. Immediately after the catheter insertion, an interactive cut-away tool allows the resident to evaluate his or her performance by visualizing the final position of the catheter in 3D.

The *ImmersiveTouch*® system has proven to be an invaluable hardware/software solution for medical education institutions and simulation centers that need a common platform to simulate multiple procedures for surgical training and performance evaluation of their medical students. Recently awarded a U.S. patent to the Board of Trustees of the University of Illinois (Banerjee et al., 2010), the *ImmersiveTouch*® technology has been licensed to a private company for commercialization.

9.1 Main contributions

In summary, the work presented in this thesis has made major contributions to the fields of Augmented Reality and Medical Simulation as follows:

- Identified the most important drawbacks of state-of-the-art augmented reality devices that are suitable for haptic medical simulation.
- Recognized the most fundamental requirements that any useful ventriculostomy simulator must satisfy to effectively reproduce the real procedure, from the identification of the surface landmarks on the patient's head to the "popping" sensation after ventricle cannulation.
- Designed and built a novel device that achieves perfect graphics/haptics collocation, combining viewer-centered perspective graphics rendering with accurate user's head tracking and high-resolution stereoscopic visualization, overcoming all problems of current systems.
- Implemented an AR haptics-based simulator that provides Neurosurgery residents the possibility of acquiring both tactile and psychomotor skills required to perform a real ventriculostomy.
- Designed a complete methodology to extract 3D models that represent skin, bone, brain and ventricles directly from real patient's CT and MRI scan data and create

a patient-specific visual/tactile simulation that can serve for both medical education and pre-surgical planning.

- Designed and implemented an efficient GPU-based algorithm for simulation of real-time deformation of elastic tissue to enhance human perception of haptic interaction.
- Validated the ability of the simulator to replicate conditions in the OR by obtaining extremely similar results in terms of both ventricular cannulation accuracy and distribution of catheter placement, compared to a recent retrospective analysis of ventriculostomies performed in real patients.
- Proved that significant improvements in performance can be obtained by using the ventriculostomy simulator to "jump-start" the learning curve of neurosurgery residents.
- Helped to determine which approaches are prone to obtain more accurate VPS placements and which ones are more likely to get higher success rates based on experimental studies conducted with the ventriculostomy simulator.

9.2 Future research

Current limitations of our ventriculostomy simulator include its inability to detect and register force feedback for sidewall collisions due to the fact that the haptics library used can only handle point-based collision detection. For instance, the module cannot produce force resistance from the burr hole walls if the catheter is laterally trans-located. Object-to-object collision detection and physics-based simulation will be considered in future.

The ventriculostomy module has been originally conceived as a “proof-of-concept” for simulation of open surgical procedures. Future developments will include other neurosurgical procedures that are technically similar from an implementation point of view, for example procedures where the instrument follows a straight line, such as vertebroplasty and lumbar puncture.

The haptic device currently used for the ventriculostomy simulator cannot reproduce torque. While not critical for a ventriculostomy simulation, torque would be indispensable for procedures such as pedicle screw placement or trephination. The use of a 6-DOF haptic device combined with more sophisticated collision detection algorithms will also be investigated to implement more complex procedures such as craniotomy, and aneurysm clipping.

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