Virtual Reality and Medicine: Technology and Applications

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Abstract

Virtual Reality is revolutionizing Medicine, from diagnosis to surgery and rehabilitation. Medical VR includes organ modeling, tissue cutting, programming toolkits, and training in palpation, anesthesia, surgery, rehabilitation and dentistry.

1 Introduction

Great advances in Virtual Reality technology in recent years have allowed its use in areas such area is medical simulations. Here VR meets a critical need for better education and training of the medical resident. First we discuss the special requirements of medical simulations in terms of dedicated i/o devices, organ modeling, or programming. Then we review some emerging applications such as diagnosis, anesthesia, surgery and rehabilitation.

2 Special Interfaces

Surgeons prefer to train on the same tools as those used in the OR. Thus medical trainees need interfaces that look and feel similar to real surgical tools. This makes force and touch feedback mandatory, which is different from other application areas (entertainment or architectural planning) where haptic feedback may not be present[Burdea and Coiffet, 1994], [Burdea, 1996].

Medical applications with haptic feedback have special requirements, since they need to be compact, light and avoid hydraulic power. Furthermore, high dynamic range is needed for high fidelity, while large feedback forces are not necessary. Such interfaces can be classified as general-purpose designs, such as the "PHANToM Master" robotic arm (SensAble Technologies Co.), or special-purpose designs for surgical training, such as the "Laparoscopic Impulse Engine" (Immersion Co.).

The PHANToM Master is illustrated in Figure 1. It is a serial feedback arm with six degrees of freedom (the translational ones are active). No gravity compensation is necessary, and the workspace accommodates wrist motion. The mechanical bandwidth is very high (about 1,000 Hz), with a maximum force exertion of 8.5 N [SensAble Technologies Inc., 1997].

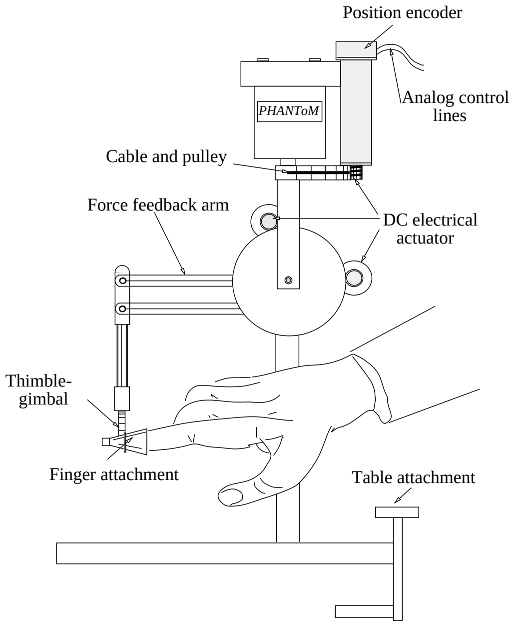

Figure 1: *The PHANToM Master (adapted from [Massie and Salisbury, 1994]). ©ASME. Reprinted by permission.*

The Laparoscopic Impulse Engine is specifically designed for Minimally Invasive Surgery (MIS) simulations. Version 3GM has five degrees-of-freedom within a $5\times9\times9$ inch workspace, as illustrated in Figure 2 [Rosenberg and Stredney, 1996]. Two degrees-of-freedom rotate by about 100^o and translated in-out by 4 in. Torques are up to 60 oz-in, and forces up to 2 lbs. The tool rotation

3 Organ Modeling

Medical simulations modeling involves organ geometrical modeling, collision detection, tissue deformation (including cutting), haptic forces, etc. Organ geometrical modeling is done mostly from visible human database of the National Library of Medicine for generic organs, or though CT/MRI for patient-specific data.

Bounding box collision detection fails for highly curved surfaces characteristic of body organs. A more suitable way is to use bounding spheres [Langrana et al., 1994], or use exact collision detection [Ponamgi et al. [1995] based on Voronoi Volumes.

Tissue deformation can be done through polygonal methods or volumetric ones. Polygonal methods use direct vertex manipulation or active surfaces [Cover et al., 1993] which are energy-minimization polygonal meshes. A special case of tissue deformation is tissue cutting, when the vertex being cut is replaced by two duplicate nodes [Song and Reddy, 1995]. These newly-created nodes are then pulled to a more stable energy configuration. Reinig's [Reinig et al., 1996] uses texture-mapped surfaces obtained from the Visible Human database to increase simulation realism.

In order to determine the forces during tissue deformation it is necessary to know the or-

Figure 2: *The "Laparoscopic Impulse Engine": a) the linear capstan design; b) overall kinematics [Rosenberg and Stredney, 1996].*

gan mechanical compliance. A simplified approach is Hooke's law. In case of heterogeneous materials (such as modeling a harder malignancy) it is necessary to use a dual-stiffness law [Dinsmore, 1995]:

$$\mathbf{F} = \begin{cases} K_1 \Delta x & if \quad 0 \leq \Delta x \leq x_t \\ K_1 x_t + K_2(x - x_t) & if \quad x_t < x \end{cases} \tag{1}$$

where x_t corresponds to the point of slope discontinuity.

Volume based surface deformation use voxels, which are nodes in a lattice spanning the volume of the virtual object. Deformation is implemented by eliminating the voxels that fall inside the volume of the surgical tool. Each voxel "resists" by a small force $\mathbf{F}_i$, with total interaction force $\mathbf{F(t)}$ and moment $\mathbf{M(t)}$ given by:

$$\mathbf{F}(t) = \sum_{i=1}^{n} \mathbf{F}_i = K_{object} \; n \cdot \frac{\mathbf{P}}{|\,\mathbf{P}\,|} \tag{2}$$

$$\mathbf{M}(t) = \sum_{i=1}^{n} \mathbf{z}_i \times \mathbf{F}_i \tag{3}$$

where K_{object} is the object stiffness coefficient, and $\mathbf{z}_i$ represents the position of voxel $\mathbf{P}_i$ inside the tool [Yamamoto et al., 1993].

4 Medical Simulation Software Libraries

SensAble Technologies Inc. introduced the "General Haptics Open Software Toolkit," an object-oriented C++ toolkit. It designed to help develop applications which use the Phantom interface and has features designed for physical modeling. These include built-in primitives (solids, buttons, slider, dial), polyhedral tri-meshes, behavior support (free-body dynamics and damping, gravity, compliance, friction), as well as force gradients, spring/damper systems, jolts, vibrations, etc..

"Teleos Toolkit" [Meglan et al., 1996] allows medical specialists to author surgical training simulations without programming. CT, MRI and the Visible Human database are used to build 3-D virtual organ models based on spatial splines. Teleos Voxel Visualizer enables real-time volume rendering, with arbitrary slicing on gray-scale (CT/MRI/Ultrasound) and color (Visible Human) data [HT Medical, 1996].

5 Applications

A very brief overview of medical applications is given below.

5.1 Tissue Palpation

Palpation is an ancient and inexpensive diagnosis procedure but requires a lot of skill (training). Peine [Peine et al., 1995] has developed a VR palpation system using an integrated force and tactile feedback manipulator (a two degree-of-freedom planar mechanism with force feedback to a finger support and a 6 × 4 SMM tactile array used to convey small contact geometry information). Human-factor experiments (300 trials) showed over 50% tumor localization with an error of ±1 mm or less.

Later Dinsmore and colleagues at Rutgers University [Dinsmore et al., 1997] developed a system for liver palpation using the Rutgers Master II (as shown in Figure 3). Human factor studies performed on 32 subjects showed a better than 90% tumor detection rate after only 5 minutes of training.

5.2 Needle Insertion for Anesthesia

Spinal anesthesia procedure involves a delicate lumbar puncture, and the needle insertion is complex. There is a "force signature" since the resistance grows as the harder inter-vertebrae ligament is traversed. A commercially available simulator from Immersion Co. incorporates a one-degree-of-freedom haptic interface [Stredney et al., 1996].

HT Medical has developed a "virtual cannula" needle insertion simulator [Merril and Kornhauser, 1996]. The system consists of a 1 DOF Immersion Needle Simulator feedback device interfaced to an SGI workstation. Graphics shows a texture-mapped arm and virtual syringe which fills with blood. This system is now used in medical education at SUNY (NY State).

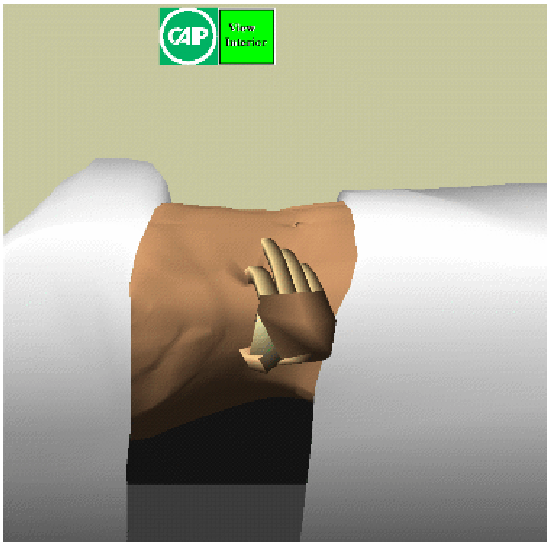

Figure 3: *Tumor localization simulation using the Rutgers Master II [Dinsmore et al., 1997].* ©*IEEE. Reprinted by permission.*

5.3 Minimally-Invasive Surgery Simulators

MIS is not "surgeon-friendly" and requires training on simulators. It is being applied for training in several subspecialties, such as angioplasty, intervention radiology, sinus surgery, endoscopy, etc.

In US arteriosclerosis accounts for about 50% of all deaths, and more patient-hospital days than any other illness. Intervention radiology is a new subspecialty in which the doctor watches a fluoroscopic screen while manipulating wires and catheters to treat blocked arteries. HT Medical has developed a prototype simulator for angioplasty (artery dilation using a balloon catheter) [Higgins et al., 1995]. The simulator uses an Immersion tactile feedback interface and SGI graphics workstation.

Ziegler and his colleagues at Fraunhofer Institute in Germany [Ziegler et al., 1996] built a sophisticated Arthroscopy Training Simulator. The trainee manipulates tool handles resembling actual surgical camera and exploratory probe, inserted into a full-scale replica of a knee. An SGI workstation moves corresponding virtual tools into the virtual knee and register any collisions. When collisions occur a four-DOF haptic interface produces resistive forces.

Chronic sinusitis affects 31 million Americans [Sluis, 1996]. Endoscopic Sinus Surgery (ESS) is used to drain the nasal cavity of fluids. It is difficult to learn and has significant risks to the patient due to the close proximity of ethmoid cavities to the eyes, optic nerve and brain. Lockheed Martin together with the Ohio State University and Immersion Co. have developed a ESS simulators as shown in Figure4 [Wiet et al, 1997].

5.4 Open Surgery

One typical procedure in open surgery is anastomosis – suturing arteries and other

Figure 4: *Endoscopic Sinus Surgery simulator [Wiet et al., 1997].*

tube-like organs. The procedure requires skill and a learning curve influencing the time a surgeon spends in the OR. Boston Dynamics Inc. has developed a surgical simulator for the teaching of anastomosis procedures. It has two Phantom interfaces with special sensing surgical tool connectors. A graphics workstation is suspended on top of a half-mirror while surgeon manipulates the interfaces under the mirror, as illustrated in Figure 5 [Boston Dynamics Inc., 1997].

5.5 Rehabilitation in VR

Performing rehabilitation in VR after surgery offers a number of advantages vs. classical exercises. The rehabilitation process is not boaring (increased patient motivation), and it allows transparent real-time data gathering. Furthermore, the flexibility of the treatment is increased at reduced costs.

An example is post-surgery hand rehabilitation research done by Burdea et al. [1997] with the Rutgers Master I. A unified system for diagnosis/rehab was built around a Sun 10-Zx workstation. Several exercises were developed using WorldToolKit graphics library, mimicking standard exercises, such as the peg-board exercise illustrated in Figure 6. Real-time individual finger forces are gathered and stored in an Oracle patient database.

Figure 5: *Anastomosis Surgery simulator [Boston Dynamics Inc., 1997]).*

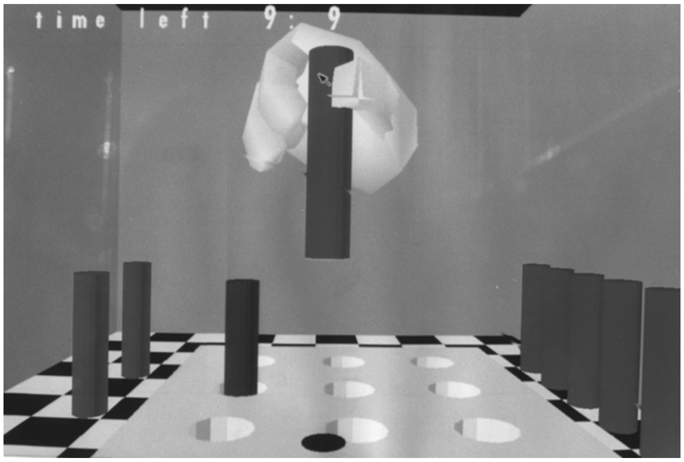

Figure 6: *Virtual reality rehabilitation exercise using a peg board. [Burdea et al., 1997] © The MIT Press. Reprinted by permission*

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