Early Results of the Development of a 3D Haptic Femur Interface for Medical Training

Charles J. Cohen, Ph.D.
Douglas Haanpaa
Gary Siebert
Cybernet Systems Corporation
727 Airport Blvd.
Ann Arbor, MI 48108
734-668-2567
ccohen@cybernet.com, dhaanpaa@cybernet.com, gsiebert@cybernet.com

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ABSTRACT: *Safe and successful surgical intervention requires careful planning and precise technical execution along with dynamic responses to observation of the surgical site during the procedure. In an ideal surgical education and training environment, repetition, reinforcement, review, and re-evaluation should speed the achievement of required performance levels, focus trainees on critical tasks, and promote the development of interoperative decision competencies. Such training should reduce medical error rates, improve the accuracy of interoperative judgments, increase efficiency, and improve patient outcomes at lower cost. In practice, surgeons in training learn how to operate by practicing, under supervision, on real patients. This subverts efficient and quantifiable attainment of the desired objectives due to uncontrollable factors such as random patient availability and diverse disease presentation. An interactive virtual surgical training environment provides a promising solution to these problems.*

A good first step for creating a full surgical trainer is the development of a fractured femur simulator that provides medical personnel with hands-on experience in managing various types of fractures without risk to a human patient. Such fractures include femoral neck (intracapsular); intertrochanteric; subtrochanteric; femoral shaft; and supracondylar. Such fractures can be spiral or transverse, comminuted (broken into pieces), open, or uncomplicated. This paper describes ongoing work to develop such a simulation, and includes the discussion of the following components:

1. *Development of a medical Haptic device tool kit, incorporating force feedback, texture fidelity, elasticity, and tissue resistance with visual associativity.*
2. *Creation of 3D reconstructions of anatomical femur data from the National Library of Medicine (NLM) Visible Human Project (VHP) that can by dynamically updated in response to user invention.*
3. *Development of a library of femur bone and tissue physical characteristics based on published data or bench analysis of cadaveric specimens (or other means) to add a functional dimension to the volumetric anatomical data.*
4. *Assembly of an integrated system architecture that delivers a realistic interactive milieu consisting of the medical trainee, Haptic tools, and a virtual reality display – the mathematical model transposed into the 3D VR image – presented to the participant.*
5. *Assessment of the computational, force feedback, and display latency as well as a Haptic and visual fidelity to judge the overall ability of the system to replicate conditions in an actual medical procedure.*

1. Introduction

Safe and successful surgical intervention requires careful planning and precise technical execution along with dynamic responses to observation of the surgical site during the procedure. In an ideal surgical education and training environment, repetition, reinforcement, review, and re-evaluation should speed the achievement of required performance levels, focus trainees on critical tasks, and promote the development of interoperative decision competencies. Such training should reduce medical error rates, improve the accuracy of interoperative judgments, increase efficiency, and improve patient outcomes at lower cost.

In practice, surgeons in training learn how to operate by practicing, under supervision, on real patients. This subverts efficient and quantifiable attainment of the desired objectives due to uncontrollable factors such as random patient availability and diverse disease presentation. An interactive virtual surgical training environment would provide a promising solution to these problems.

Traditional surgical training programs seek to accomplish multiple goals including the acquisition of broad surgical knowledge, diverse operative experience, expert technical dexterity, and the ability to respond to unforeseen surgical or anatomical anomalies with extemporaneous creativity and flexibility in a psychologically stressful environment. Current training methods rely almost entirely on supervised practice on real patients and are subject to the vagaries of timing, patient availability, and disease presentation. Inexperienced trainees face the daunting task of performing complex and technically challenging procedures under the watchful eye of supervising surgeons who must continuously balance the paramount needs of patient care against the training requirements of the surgical resident. An analogy in the airline industry would have a novice pilot flying a 747 filled with passengers across the Atlantic Ocean without having had the opportunity to practice on a simulator or fly an empty plane first.

Of course, the public would never tolerate such excessive risk-taking in aviation, even as most consider the apprenticeship model to be the state of the art in surgical training. Simulation-based training systems have only recently been postulated as training alternatives for surgeons, and those few systems that have been developed are very primitive. This paper presents the development of a prototype surgical simulation training system. This system will offer a safer, more efficient, and more economical way to train and credential surgeons.

Because the cost of training surgical residents is extraordinarily high, not to mention the costs for military medical personnel to maintain proficiency, the economic basis for research and development of surgical simulation systems is compelling. One group has estimated that the incremental cost of training chief surgical residents associated with extra operating room time alone amounts to about $58 million annually [Gorman, 1999]. Efforts to decrease the cost of health care and of training are embodied in recent congressional actions that threaten these existing models of surgical education. The Balanced Budget Act of 1997, Public Law 105-33, will result in the loss of hundreds of millions of dollars that would have otherwise been used to support graduate medical education through the Medicare program. These budgetary pressures continue to mount in the private sector as well, as health maintenance organizations face rising costs and declining revenues. Clearly, successful efforts to develop virtual surgical training environments will be rewarded by a strong return on investment only if they are demonstrated to train surgeons as well as or better than traditional methods and at lower costs.

There is also increasing pressure to reduce medical errors. The Institute of Medicine recently reported that tens of thousands of medical errors occur each year; surgical misadventure was highlighted in the first paragraph of the report's executive summary [Kohn, 1999]. Recommendation 7.2 of the report calls on professional societies to "recognize patient safely considerations in practice guidelines and *in standards related to the introduction and diffusion of new technologies…*" [emphasis added]. The cost in human and financial terms of surgical errors should not be underestimated.

Interest in the use of artificial environments for training and certification to improve patient care is substantial, and validated precedents in the airline industry and the military suggest that medical applications have great potential (see [Issenbert, 1999], [Office of Naval Research, 1973], [Dusterberry, 1975], [Kilby, 1998], [McDonald, 1998], [Torkington, 2000], and [Smith, 1999]). Development has been strongest in the area of laparoscopic surgery, where a number of simulators and training programs have been reported. However, most of these utilize standard laparoscopic instruments applied to inanimate objects. Participants are appraised by an observer or by capturing motion data (see [Derossis, 1998], [Rosser, 1998], and [Rosser, 1997]). The use of virtual reality for surgical simulation has only recently been attempted for laparoscopic interventions (see [Chaudhry, 1999], [Gallagher, 1999], Ota, 1995], and [Wilson, 1997]). These systems generally do not include force feedback, which limits their ability to simulate the tactile feedback that has been documented during actual laporoscopic surgical procedures [Bholat, 1999], and virtual reality representations have been inconsistent and require hardware that does not perform well for extended periods of time.

Very recently, systems incorporating force feedback haptic devices have begun to emerge, but for the most part, these are prototypes that have not been studied recently. Using a virtual laparoscopic trainer, one group has reported the ability to document degradation in simulated operative performance accompanying sleep deprivation in a prospectively designed study [Taffinder, 1998]. These preliminary findings suggest that further development of surgical simulation technology may ultimately permit the use of these systems for certification and credentialing as well as training [O'Toole, 1999]. However, the ability to simulate *open* surgery requires a more integrated approach to provide convincing force feedback responses to interactions with a realistic virtual image.

A good first step for creating a full surgical trainer would be the development of a fractured femur simulator. This would provide medical personnel with hands-on experience in managing various types of fractures without risk to a human patient. Such fractures would include femoral neck (intracapsular); intertrochanteric; subtrochanteric; femoral shaft; and supracondylar. Such fractures can be spiral or transverse, comminuted (broken into pieces), open, or uncomplicated. This paper discusses such a simulator for used by the DoD and the commercial medical community.

2. Using Force Feedback

Force feedback forms the basis of this technology (see [Jacobus, 1995] and [Jacobus, 1997]). Through work done at Cybernet, the devices developed have a powerful software library, the CyberImpact™ Software Development Kit (SDK), which allows an application developer to assign physical properties to virtual objects and incorporate force feedback into end-user applications. The user can interact with and dynamically manipulate these objects in 6 degrees-of-freedom (*DoF) using the force feedback device. One of the key aspects of the CyberImpact™ SDK is its ability to provide all the tools necessary to create new Haptic effects as the needs arise.

The CyberImpact™ SDK has two primary functional components: the Application Programmer Interface (API) and the Haptic Device Server (HDS). The API is grouped into three distinct function sub-libraries: Force Feedback Effects Library (FFELib) with source code; Haptic Library (HAPLib); and Controls Library (CNTRLib):

- **FFELib** is a convenience library containing commonly used force feedback effects. All of the functions in the FFELib are constructed using the advanced tools in the HAPLib. The FFELib source code serves as a starting point for the creation of more complex force feedback effects. The FFELib will be continuously extended to include innovative and specialized efforts.
- **HAPLib** is an extensive force feedback API that facilities the creation of a wide range of Haptic effects. It is designed as a tool set through which all of the facilities of a force feedback device are accessible. The HAPLib is device independent and can be used to program a variety of devices, which may be custom designed or vendor provided.
- **CNTRLib** provides an interface to the control architecture that the HDS server uses. The CNTRLib API is used to individually read and set values of each control. In addition, certain Haptic effects and functionality are accessible only through this layer. The HAPLib is written using the CNTRLib API.

The HDS is the "brain" of the force feedback system. Just as applications use a graphics subsystem to render visual information, the HDS is used to render Haptic information. Low-level details of the device server are hidden from the user through the use of the CNTRLib, HAPLib, and FFELib. In short, the device server takes care of all the low-level hardware communication and control tasks so the developer can concentrate on creating innovative Haptic effects. The client application communicates with the HDS using an abstract API called the Communications Library (CommLib).

Two attributes of the CyberImpact™ SDK make it useful as the foundation for medical simulation. The first is the method of communication between the user application and the HDS (provided through the SDK). To maximize the applicability of the CyberImpact™ SDK, the end application and the HDS can reside on one or more computers. By distributing the computational tasks among several computers, a wide variety of Haptic effects can be implemented easily without burdening the application platform with added computational load associated with force feedback. Communication between software modulates can be effected using function calls, sockets, pies, shared memory, or any other method of inter-computer communications.

The second attribute is the geometric engine that is a part of the HDS. This engine, specifically the transformation and object functions, gives the user the capability to instantiate virtual Haptic objects, the positions and/or orientations of which depend upon the Haptic device axes. These virtual objects can interact with other instantiated virtual objects, generating forces that propagate back to the device axes themselves, generating force feedback. The transform hierarchy is completely configurable, with each transform being static changing with a constant velocity and/or acceleration, or changing in response to the motion of a Haptic device axis.

3. Modeling and Simulation of Tissue Deformation

In medical simulation, the forces supplied to the Haptic system result from the elastic nature of tissue deformation. Computing tissue deformation and the resulting tissue reaction forces is one of the most critical aspects of a medical/surgical simulation system. The computational tissue model determines the deformation field that the user sees and the reaction force that the user feels through the Haptic system. Computing tissue deformations and forces requires: 1) a computational tissue model and its numerical implementation; and 2) a database of experimentally determined tissue material properties spanning the range of tissue behavior that can be used in the model.

Almost all numerical implementations of tissue mechanics models are performed using the finite element method. A substantially general, although not completely general, model of tissue mechanical behavior accounts for nonlinear tissue elastic properties, large deformation of tissues, residual stresses σ^R in tissues, active stresses σ^a generated by tissues (skeletal, smooth, and cardiac muscle), and dynamic inertia forces [Fung, 1993]. In the finite element equation below, stresses are incorporated as force vectors. The nonlinear stiffness and large deformation components are incorporated as two components of the stiffness matrix K:

$$[M]\{\ddot{u}\}+([K^{tangent}]+[K^{nonlinear}])\{u\}=\{F^{applied}\}+\{F^{active}\}+\{F^{residual}\}+\{F^{nonlinear}\} \quad \text{[Eq. 1]}$$

where M is the mass matrix, $K^{tangent}$ is the tangent nonlinear material portion of the stiffness matrix, $K^{nonlinear}$ is the portion of the stiffness matrix resulting from nonlinearity, $F^{applied}$ are the applied forces, F^{active} are active forces due to muscle contraction, $F^{residual}$ are forces resulting from residual tissue stress, and $F^{nonlinear}$ are residual stress due to tissue material nonlinearity. As part of a group effort, Dr. Hollister has recently developed and implemented numerical algorithms to solve equation 1 for modeling skeletal muscle [Palmer, 2000]. This equation is the most general elastic model for soft tissues; i.e., all the elastic behavior of soft tissues is embodied in this equation or simplifications thereof. Drs. Hollister and Feinberg also have substantial experience creating anatomic finite element models from Visible Human Data (see [Feinberg, 2000] and [Hollister, 2000]). In fact, they created a mandibular condyle biomaterial design directly from the Visible Female data using an image-based approach [Hollister, 2000]. This task is required for fracture femur simulation, which is the examination/surgical procedure to be selected as a target application for the Phase II effort.

4. Modeling and Simulation of Human Anatomy

The augmented Visible Human datasets being produced by the University of Michigan Visble Human Project (UM-VHP) provides a unique resource for this surgical simulation demonstration and product prototyping project [University of Michigan, 2003]. The UM-VHP is based on the NLM VHP image datasets, which currently include male and female voxel-based datasets. The current male dataset has a spatial resolution of 250 μm in the x- and y-axes and 1,000 μm in the z-axis for the male and 330 μm spatially isotropic voxels for the female [University of Michigan, 2003]. The spectral data content for these datasets is normalized to a three-color data palate of 16 bits. The UM-VHP specializes in scalable Visible Human navigation and visualization solutions for the educational application space, including surgical trainees [see [Bookstein, 2000] and [Ade, 1998]). The UM-VHP is also annotating every voxel in the dataset with region and lanmark (point, line, and surface) descriptors. The system described here is an extension of these efforts.

Two additional datasets are of value in this work. The first is the Visible Human male film scan dataset, which offers increased spatial, spectral, and texture resolution in two of three axes. The dataset will be re-sampled to a cubic voxel of 150 μm in the z-axis using spatial/spectral classification and interpolation tools available. Target cubic data densities for the voxel datasets will be a core of 500 MB floated into an apodization volume boundary cube that allows landmark structure, region, boundary layer, and tension gradient fields to be modeled. The UM-VHP will also request the newly produced 150 μm isotropic voxel Visible Human Male-II head and neck dataset from Dr. Victor Spitzer of Colorado, who has produced a new, higher-quality dataset of the head and neck region under contract from NLM. These voxels will be labeled with tissue property characteristics including a tensor descriptor of stress and stain moduli giving an isotripc/anisotropic tensor field indicator. To avoid database look-ups, all data needed for the simulation can be embedded into an extended voxel data structure that will be created as a standard model in collaboration with Colorado, Stanford, and the NLM Insight Software Visible Human toolkit consortium. Pre-rendered surface and volume visualization libraries for the anatomic regions of interest will be used as starting points for the autostereoscopic visualization mapping update calculations.

5. Virtual Reality Display

The visual display constitutes the final essential component of a surgical simulation system. We will take advantage of our OpenSkies Simulation Engine to get a quick start on this project. Using this system, we are able to create a immersive virtual world for surgical training. The following is a brief description of the OpenSkies software.

Cybernet created a simulation system bearing the OpenSkies name and embodying the same spirit. The OpenSkies training and simulation system is a truly open and realistic distributed training and simulation system for the high performance PC. As the name suggests, this system is designed to lift the limits of proprietary formats and protocols and expose all necessary information to the simulation enthusiast.

Documented network communication protocols, loadable simulation modules, public domain terrain or other feature sets, and standards-based object representations are all essential parts of the OpenSkies movement. These standards include such interfaces and APIs as OpenGL, HLA (a military distributed simulation networking protocol) and SEDRIS (a military standard data interchange mechanism designed to facilitate the interchange of synthetic environments between simulators).

The OpenSkies system is a state-of-the-art PC-based training and simulation software package that makes use of recent advances in consumer level computing hardware. Designed from the ground up as a general purpose training and simulation toolkit, many different types of training simulations are easily created. OpenSkies is designed to support such features as force feedback, accelerated 3D graphics, multi-user networking, scenario development and performance analysis. Open source is provided for each of these features with a standardized and documented interface to make creating customized content easier for potential developers and instructors.

With all the capabilities of OpenSkies combined, they create a system capable of providing a realistic and immersive training or simulation experience. This modified system created the preliminary surgical environment.

6. Early Results

With all the capabilities of OpenSkies are combined, they created a system capable of providing a realistic and immersive training or simulation experience. This system was easily modified to be used for surgical environments. The details listed below are the general capabilities for surgery environments (as depicted in Figure 1).

Training
- Realistic cause/effect scenarios supporting real surgical training exercises. Instructors can easily create scenarios for training.
- Recording and Playback of entire training sequence for later analysis by the student and instructor.
- Automated Performance Analysis for rating students as well as instructor analysis.

Graphics
- OpenGL hardware accelerated graphics with 16 bit color.
- Screen resolutions of up to 2048x1280 with full graphics and frame rate - up to 30 Hz, depending on graphics hardware.
- Real 3D instruments created from real photography. Supports HMD's and shutter glasses.
- Multiple view support - You can have multiple out the window views or make a whole room your simulation center.
- Moving map display for tracking that uses real digital maps.
- Open Object Representations: VRML, OpenGL, etc.

Open Source
- Loadable Simulation Modules: Dynamically loaded libraries (DLLs), based on open C++ source code, that describe behavior and appearance of all sim objects.
- Real Aircraft Behavior Models: T34 single engine aircraft and TH57 helicopters.
- Real Audio: DirectSound and prerecorded ATC. Plane to plane chat is soon to come.
- Programmable interactions between objects. You can implement collisions, damage and even more complex AI interactions over the net between players and vehicles.
- Works on all force feedback DirectX compatible devices including I-Force® controllers such as CH

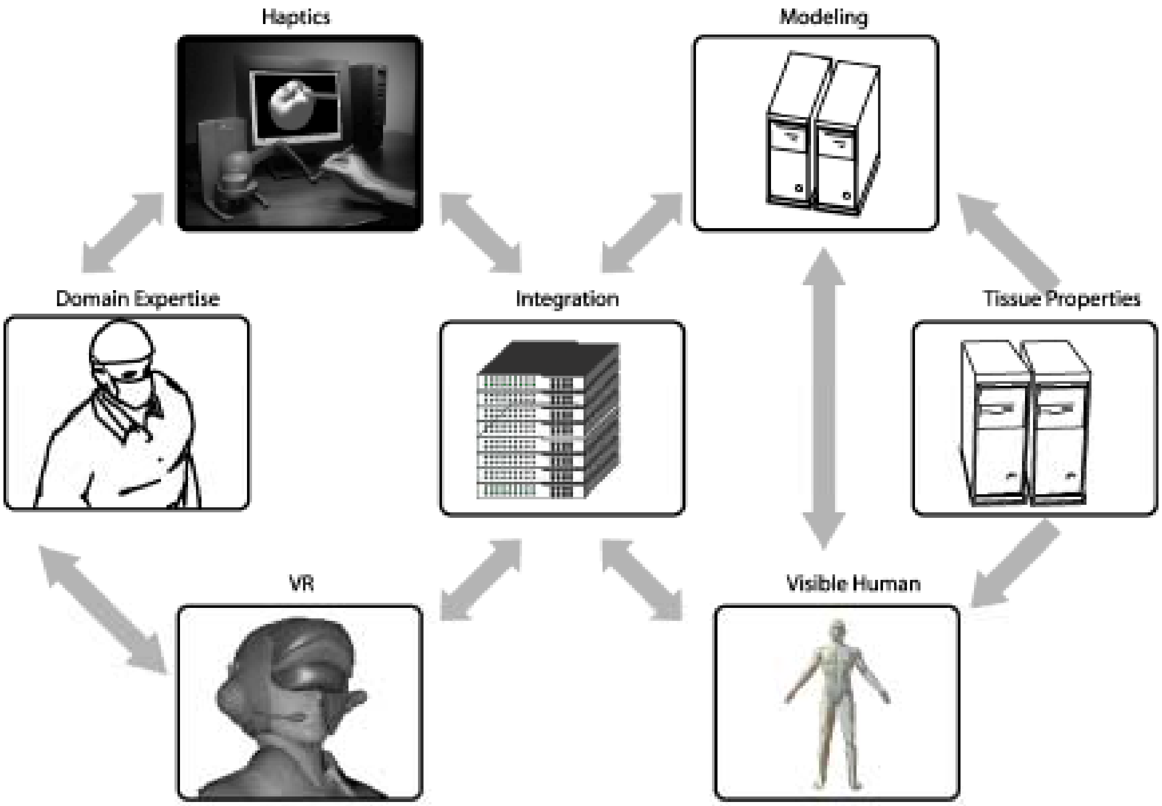

Figure 1: Interaction of System Components for Haptic Interface Development for Surgical Training

Products®, Logitech®, and ThrustMaster® devices as well as Microsoft® force feedback devices.

Multi-Player Networking

- Communications protocols: Supports the military's High Level Architecture (HLA) standard for simulation networking and multiplayer capability across the Internet. Therefore this system can be used by military surgical corps.
- Promotes interoperability between different simulations. The HLA communications system API and binaries are freely distributed - no licensing fees required.

The principal goal of this effort is to produce an integrated examination/surgical simulation system prototype incorporating a force feedback Haptic interface, modeled tissue properties, and a visual display that replicates the interactions of a resident working on a live patient. The five specific aims are:

1. Develop a medical Haptic device tool kit, incorporating force feedback, texture fidelity, elasticity and tissue resistance, with visual associativity.
2. Create 3D reconstructions of anatomical femur data from the National Library of Medicine (NLM) Visible Human Project (VHP) that can by dynamically updated in response to user invention.
3. Develop a library of femur bone and tissue physical characteristics based on published data or bench analysis of cadaveric specimens (or other means) to add a functional dimension to the volumetric anatomical data.
4. Assemble an integrated system architecture that delivers a realistic interactive milieu consisting of the medical trainee, Haptic tools, and a virtual reality display – the mathematical model transposed into the 3D VR image – presented to the participant.
5. Assess computational, force feedback, and display latency as well as a Haptic and visual fidelity to judge the overall ability of the system to replicate conditions in an actual medical procedure.

On performing medical examination of the femur, the trainee will note the tactile sensation of the bone and tissue. The use of a haptic device will help the medical professional to feel different types of fractures, as well as allowing interactions with the major arteries, veins, and nerves, and also with muscle, skin, and related tissues.

For our preliminary work will extend the functionality of the existing device to surgical instruments that will be actuated to simulate the physical configuration and forces that a surgeon feels during an actual operation. Surface representations of the surgical instruments will be constructed for display in the visual system along with the tissue models. The end-effectors will require additional controlling software to be written to simulate the surgical tool's interaction with tissue and bone. Cutting, spreading, squeezing, and clamping interactions will be added to the currently modeled interactions of touch and deformation. To account for rotational as well as translational forces, we will explore the development of three additional degrees of freedom for force feedback beyond the three incorporated into the current Haptic device.

The desire to produce an integrated prototype is an ambitious goal. The major overriding issue is the sampling rate differential between tasks and the need for an integrated software API that can allow for the diverse requirements of computational simulation to be handled uniformly. The need for tactile feedback at 1,000 Hz sets all the other system parameters and limits. The Visible Human-enhanced computational model thus needs to be updated at a 2,500 Hz clock rate. An appropriate high-end personal computer will be used for this purpose (with a shared-memory cluster of at least four CPUs, if needed). At the other extreme, surgical instrument motions will need to be updated at only 10 Hz. This rate will permit straightforward visualization integration. The stereo visualization update will need to occur at low frame rates (30 fps), and can be enabled by a combination of reasonably priced graphics hardware subsystem boards coupled to stereo visualization software modules. These two computational subsystems will be integrated into one heterogeneous computing cluster.

Computer hardware, device hardware, software, and application integration presents a demanding challenge to be overcome. Our current approach involves breaking this challenge into four integration subtasks and one global integration demonstration task. The subtasks include: 1) the enhanced Visible Human dataset computational model integration subtask; 2) the enhanced Visible Human computational model-haptic integration subtask; 3) the visualization display-haptic integration subtask; and 4) the enhanced Visible Human computational model-visualization display subtask. The global integration demonstration task will be directed towards integrating results from the four subtasks.

7. Evaluation

The ability to faithfully recreate the surgical operating room environment in a realistic, interactive, ethereal realm is a complex task. The metrics that will be used to judge the success of the system must accurately and reproducibly correlate to real surgical procedures.

Four evaluative elements will be integrated into the project to judge its effectiveness:

1. We will assess whether full 6 DoF motion has been achieved with the system. The physical attributes of the prototype haptic devices must correspond in look, feel, and function to those used in actual medical procedures. Medical instrumentation is widely available and will be used extensively in the prototyping of the haptic devices. These hybrid devices will be built with a chimeric approach, fusing the manual portion of actual medical instruments to the force feedback sensor/actuator elements of the haptic components.

2. The devices must be constructed such that their connection to the force feedback portion of the integrated system permits the normal and customary orientation of the devices. We will determine whether the haptic medical instruments can reach the entire work envelope and quantitate the scope of environmental freedom using the Haptic device compared to medical personnel performing in a real environment.

3. The reconstructed femur anatomy must be imbued with enough tissue properties and modeling knowledge to provide a high-fidelity sensorimotor interface for the trainee.

4. Data communications among the component subsystems of the integrated prototype must occur at a rate high enough to convey realism. We will assess the ability of the visual display of the simulated and modeled system to provide a realistic image that responds dynamically to interaction using the haptic devices with acceptable latency and synchronization.

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Author Biographies

CHARLES COHEN has been working in the fields of image processing, robotics, human-computer interaction, and artificial intelligence for over a decade. He is currently the Vice President of Research and Development for Cybernet Systems Corporation. He has been the project manager for many projects for the United States Armed Forces (Air Force, Navy, and Army), National Aeronautics and Space Administration, and other government agencies. Dr. Cohen's current research interests are in gesture recognition, image processing, estimation theory, system integration, visual communications, machine vision, and perceptually coupled systems.

DOUGLAS HAANPAA is currently the technical team manager for Cybernet's Virtual Reality group. He is responsible for the management of OpenSkies. He contributed much of the design of this product as well as implementation of flight dynamics, collision, and force-feedback algorithms. He also acted as a key designer for many of the OpenSkies subsystems including the terrain parsing/rendering/LOD system, scenegraph, weather model, and parallel thread/timer system.

GARY SIEBERT contributed to a variety of projects ranging from electrical & digital design / implementation to GUI programming. Specific projects include: 6DOF Force Reflecting Hand Controller, Fast Learning Neural Network techniques, Data Acquisition devices, Small Robot control systems, Remote Controlled Vehicle implementation, Development of Intelligent Motor Drivers, 7DOF Large Work Volume Haptic Input Device, and Production Force Feedback Devices for Flight and Driving Simulation. Mr. Siebert has been the principal design engineer of motion control electronics for haptic input devices. These designs range from high fidelity control systems for pneumatic and electromechanically controlled devices, to low cost high volume production devices.