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Haptic Rendering of Volumetric Soft-Bodies Objects

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Introduction

The interfacing of force-feedback devices to computers adds touchability in computer interactions, called computer haptics. Collision detection of virtual objects with the haptic interface device and determining and displaying appropriate force feedback to the user via the haptic interface device are two of the major components of haptic rendering. Most of the data structures and algorithms applied to haptic rendering have been adopted from non-pliable surface-based graphic systems, which is not always appropriate because of the different characteristics required to render haptic systems.

We use advanced computer modeling and coding techniques to implement (on 266 MHz PC/NT): 1) Haptic rendering of 3D volumetric objects using occupancy-map algorithm (OMA) for collision detection. This is an extension of currently available OMA for solid non-deformable convex virtual objects. 2) Chainmail algorithm (CMA) for generation of the real-time forces feedback while allowing deformation of the soft-bodied object to occur. This is an enhancement of currently available CMA used for calculating the behavior of convex surface virtual objects. Using these techniques we establish the viability of being able to work with volumetric soft-bodied objects.

Occupancy-map Collision Detection and Chainmail Algorithms

The very first step of interacting with virtual objects is to establish a collision with the virtual object. In a haptic virtual reality system (HVRS) an interaction with a virtual object is done by "touching" the object using a haptic interface device (in our case this is the PHANToM stylus). For a real-time HVRS this implies that a very efficient collision detection algorithm is essential, since otherwise the system would be useless.

The virtual environment and virtual objects are stored in memory in a three dimensional array called an occupancy map. When the occupancy map is initialized, each position in the map is set to –1 meaning that it is unoccupied. When a virtual object is added to the scene, the appropriate positions in the occupancy map are set to 0. The borders of the virtual scene follow this same pattern as well.

Similar to the movements of a chained armor, the chaimail algorithm provides the minimum, maximum, and "shear" distances that a voxel and its linked neighboring voxels are allowed to move. Once the OMA determines a collision, the CMA determines the geometry of the neighboring vertices including the direction(s) of the movements. Figures 1 and 2 clarify these concepts. Whenever the distances are violated between two voxels, the neighboring voxels are adjusted to compensate for the discrepancy. This process is recursively implemented until all the voxels in the system reach stability, i.e. meet the minimum, maximum and shear distance criteria for x, y and z directions.

At any given time, the position of the PHANToM stylus and the occupancy map are used to determine a collision between the voxel at that position and the stylus tip. Further more, the direction of approach and "chain mesh" of the CMA are taken into account to resolve the collision with "ripple effects of other voxels" and the deformation (movement of the voxel) that occurs due to the collision.

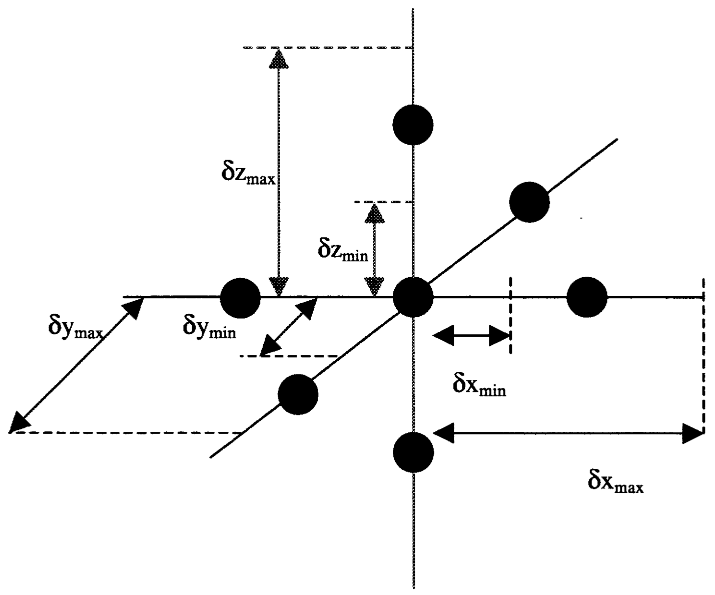

Figure 1. Chainmail Model Nearest Neighbor Distance

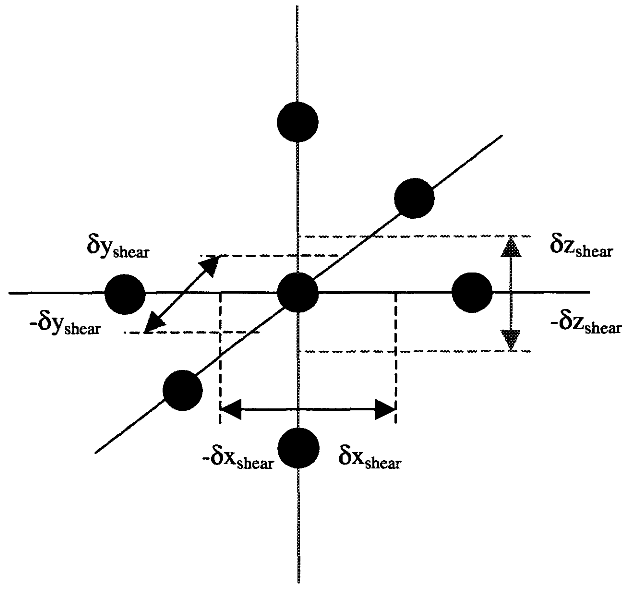

Figure 2. Chainmail Model for Shear

<u>Issues encountered</u>

Stability of the system

In surface based haptic rendering with thin objects, phantom's virtual position passes through the surface and becomes closer to the far edge than the edge it originally passed through. Since the force vector is proportional to the distance of the proxy and the nearest surface, this causes the change in direction of the force. Creating a virtual proxy that remains on the surface solved this problem. Figures 3 and 4 explain the concept and the solution.

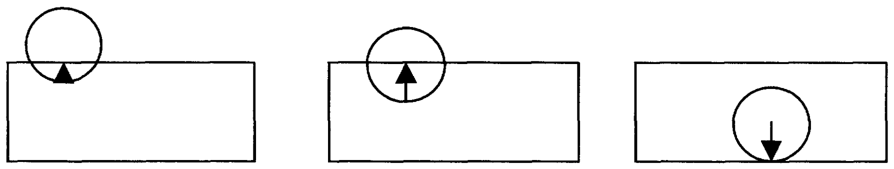

Figure 3. Surface Based Haptic Rendering without proxy

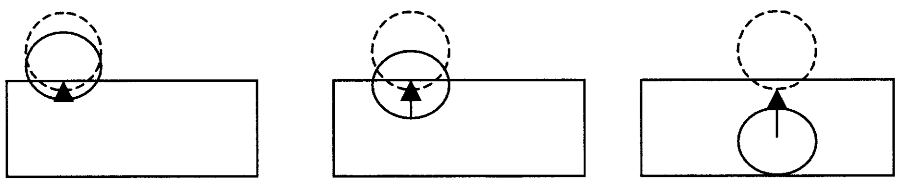

Figure 4. Surface Based Haptic Rendering with Proxy

Similarly with volumetric rendering technique the contact is momentarily lost if the force is strong enough to bounce the phantom away from the surface, although the user is still pushing towards the surface. The net effect is that the phantom position and the surface voxel pass through each other (Figure 5). Since there is no contact with the voxel, there is no force feedback from the haptic device and since there is no pressure against the surface, the voxel relaxes outward. To help resolve this problem the collision was checked at the location of proxy and at the six directional points at a fixed radius distance from the proxy until the contact is made.

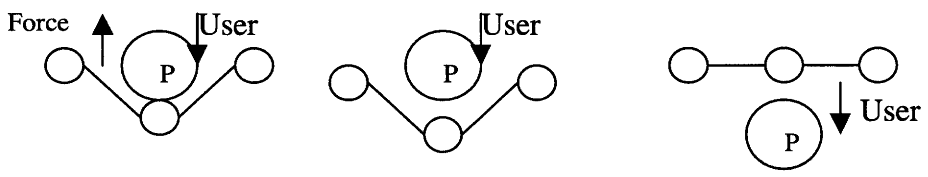

Figure 5. Bounce Surface Contact Instability

Relax Stability

The relax stability problem is believed to be caused by the bounding of the voxels together. When the voxels attempt to move to their lowest energy relationship to their neighbors, they actually impose energy on the system as a result of their movement. The result is similar to a string that has been drawn tight between two points and then plucked. If this occurs in a system without energy loss the string will vibrate forever. This system is visualized in figure 6. We found that our system required damping of the relax function such that only a small movement to the desired location occurred during any relax step. Otherwise the entire virtual object will vibrate. Interestingly, the vibration does not cause problems with the haptic rendering, but does cause an unpleasant visual effect to the simulations.

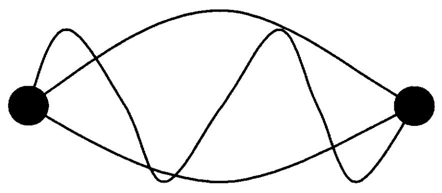

Figure 6. Stable Vibration States of Bound String

Conclusion

The hardware requirements for this implementation make the technique computationally expensive, but allow for haptic presentation of materials with non-homogenous internal behavior. The average memory usage for this system is between the range of 11.5 to 12MB for a scene of 11,200 polygons. Although this would indicate a need for substantial memory requirement, the continuing decline in price of memory chips would offset the cost.

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Volume Rendering with Haptic Interaction

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Abstract

This paper describes a new interface, which supports volume rendering with haptic interaction, between a haptic device and the application. The currently available GHOST SDK represents only the haptic environment as a hierarchical collection of geometric objects. We have developed a volume-based GHOST Application Programming Supplement Interface Library (APSIL) for volume visualization which is based on voxel representation, rather than on geometric representation. APSIL is an extension of the GHOST SDK and consists of some new classes to process volume haptic rendering and compute interaction forces according to the density of the volume data, velocity of movement, and environmental factors. Applications communicate with the haptic device through our APSIL library on a higher-level interface based on GHOST SDK.

1. Introduction

An important requirement for both volume visualization and 3D modeling systems is the ability to interactively manipulate complex three-dimensional models in an intuitive manner. The mouse has been the main input device for volume visualization systems. As it is not convenient for the mouse to provide intuitive interaction, haptic interaction can provide the user with an intuitive set of tools for exploring and modeling objects. Haptic interaction relies on interactive force feedback and rendering to allow a user to quickly explore and modify a volumetric scene. Haptic devices allow physical interactions with virtual environments, enhancing the ability of their users to perform a variety of complex interaction tasks.

Haptic interaction for volume graphics has been applied to many application areas. In computer-based surgical simulation, volumetric object representations, real-time volume rendering, and haptic feedback were used for simulating arthroscopic knee surgery [1]. In molecular docking studies, a robotic arm was employed to supply molecular interaction forces [2]. In another application, a haptic device was utilized as a tactile tool to explore and sculpt synthetically generated voxel-based objects [3]. A medical planning and training system [4] has also been developed which simulates knee palpation through the use of visual and haptic feedback.

Volume rendering with haptic interaction, based on volumetric objects, would be particularly useful when the user attempts to: precisely locate a feature within a volume; fly inside a volumetric object; understand the spatial arrangement of complex three-dimensional structures, or tactilely operate on an object. However, it has not been fully explored. In this paper, the development of the interface between a haptic device and its applications based on voxel objects is described.

2. Haptic Interaction for Volumetric Objects

The tactile feedback for sensing virtual volumetric objects is involved in the haptic rendering - the process of feeling virtual objects. In general, the interaction required to control haptic interfaces can be described as a combination of real time volume rendering and a servo control loop. A high level description of this servo loop involves the following:
1: Locate the user's finger position with respect to the virtual environment
2: Calculate a reaction force vector based on physical laws of the virtual environment
3: Apply that force vector to the user's finger
4: Go to 1

The most difficult step is step 2. For this step, several researchers [2,3,4,5,6,7] have proposed methods to simulate static, dynamic, viscous friction and texture. Unlike previous methods, our implementation creates these effects solely based on the volume voxel density and its properties. A relationship $\mathbf{f} = \mathbf{f1(d,p)} + \mathbf{f2(v)}$ is used to calculate the reaction force. That is, the reaction force in our model is the sum of the static resistant force **f1** and the damper force **f2**. The force **f1** can be calculated by a transfer function according to the properties **p** of the volumetric objects, such as friction and stiffness, and the density **d** of the volumetric object at the endpoint of a PHANToM, which is determined by using tri-linearly interpolated neighbor densities. The force **f2** can be calculated by the transfer function based on the velocity **v** of the user moving into or inside the virtual objects.

3. GHOST Application Programming Supplement Interface Library (APSIL)

Traditional methods for producing a convincing haptic rendering have mainly utilized scenes comprised of geometric primitives such as polygons, spheres, and surface patches. These investigations have generally focused on simulating realistic interactions with static and dynamic collections of geometric objects given the capabilities and limitations of haptic devices. The haptic device used in the development of visualization systems is the PHANToM. Its development environment, GHOST SDK, is a C++ object-oriented toolkit that represents the haptic environment as a hierarchical collection of geometric objects and spatial effects. The GHOST Application Programming Interface (API) enables application developers to interact with haptic interaction devices and create haptic environments at the geometric object level. However, volume visualizations are not based on geometric objects, but on voxel-based volumetric objects. A GHOST Application Programming Supplement Interface Library (APSIL) has been developed to support haptic interaction, to compute the interaction forces between the terminus of the haptic device and the voxels, and then to send forces to the haptic interaction device.

Applications communicate with the haptic device through the APSIL interface library. This library both supports all the functions based on the GHOST SDK and acts as a supplement of GHOST SDK. The APSIL library allows users to define objects as a collection of primitive objects - based on voxels. Object hierarchies and material properties such as friction and stiffness may also be defined.

The APSIL library is the user-level extension of the GHOST SDK classes and is written in the C++ programming language, consisting of a set of C++ classes:

gstNode —— gstTransform —— gstVolume* —— gstVolumeBody*
gstEffect ——- gstVolumeEffect*
(* = subclass we created)

The class gstVolume* is created by subclassing from gstTransform class, while also gstVolumebody is created by subclassing from gstVolume class. The class gstVolumeEffect* is created by subclassing from gstEffect class. The resulting new classes, gstVolume*, gstVolumeBody*, gstVolumeEffect*, are added to the GHOST SDK class TREE.

To create a new subclass, gstVolumeEffect*, of gstEffect class, the important method that needs to be overloaded is calculationofVolumeEffectForce(), which is used to determine the resistant force at the endpoint of a PHANToM, when the PHANToM touches the volumetric object. Also a set of methods is provided in subclass gstVolume to handle the different properties of volume object, such as static friction, dynamic friction, spring and damping. At the same time, another set of methods has been developed in the subclass gstVolumeBody, for handling the density of every voxel.

4. Implementation

The method described above, based on the APSIL library, has been implemented on both a PC NT and a Silicon Graphics Onyx with PHANToM haptic interface. This interface provides force-feedback for surface and volume exploration and operation, understanding complex structures, flying inside virtual objects, and transmitting the sensation of touching material by hand. Additionally, an application on a responsive workbench has been developed, by which the information of the data set can be better understood by stereo imaging along with the force feedback provided by a PHANToM device. To date, some demos of volume rendering with haptic interaction with the APSIL library have been developed, including a $160 \times 160 \times 17$ voxel CT data set of a lobster, a $256 \times 256 \times 93$ CT data set of a human brain (See figure 1), and a $256 \times 256 \times 109$ MRI data set of a human head.

Furthermore, special consideration was taken to provide force feedback without producing unwanted vibrations by a self-adapted algorithm. For example, when the density field changes substantially, especially from empty space to dense object within one or two voxels, this self-adapted algorithm will offer the increase of feedback force steadily according to the change of this force.

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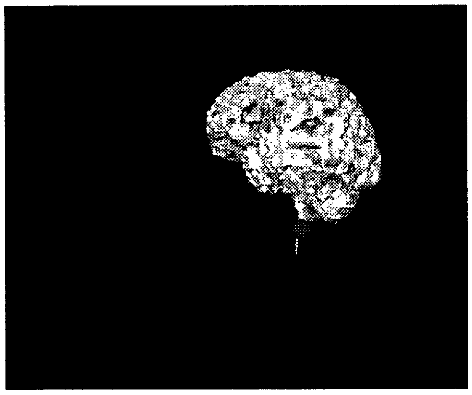

Figure 1: *An example of haptic interaction applied to a brain*

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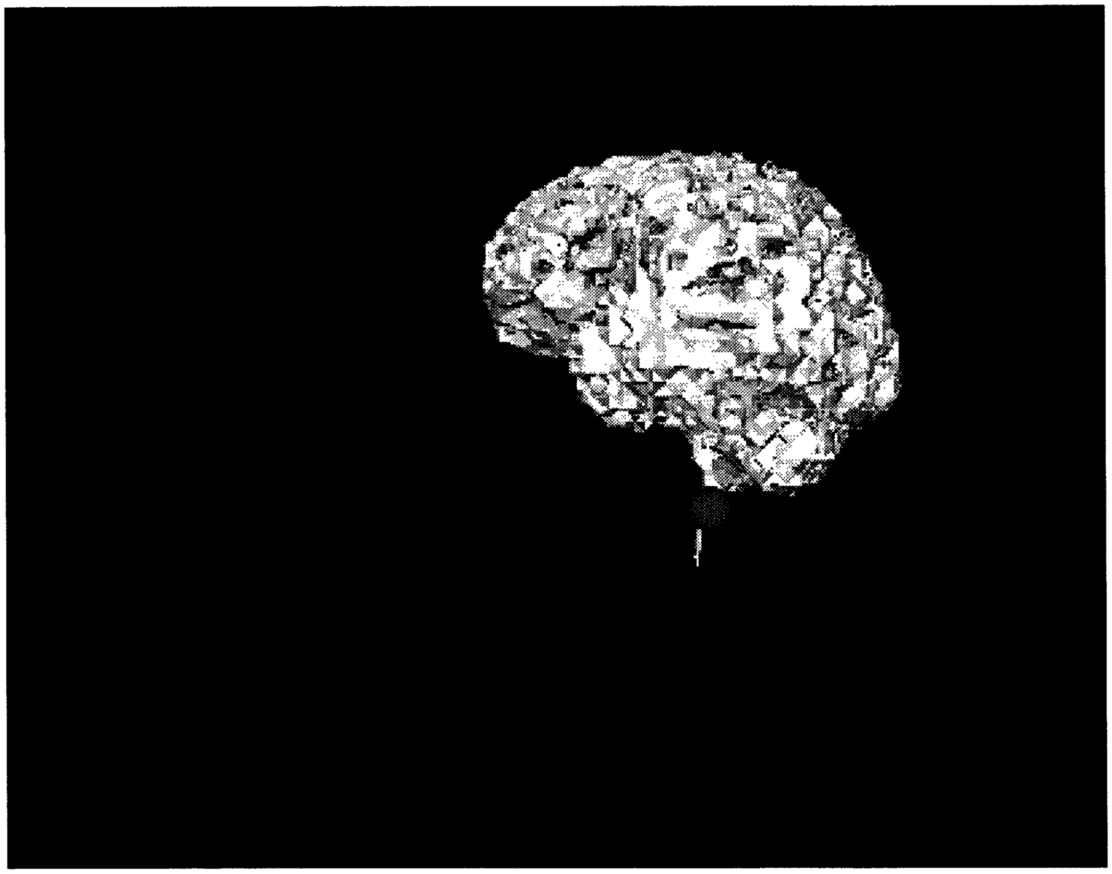

Haptic Volume Rendering in Different Scenarios of Surgical Planning

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Abstract This paper presents ongoing research in the field of surgical planning using a PHANToM force feedback device. Previous research and use of haptic systems in medicine mainly concentrated on surgical simulation. Since preoperative planning and, especially, segmentation are prerequisites for simulation, they are relevant for physicians. Experience from projects in virtual liver tumor resection and heart surgery indicated that segmentation and measurements are desired functionalities. For that, a general and adaptable haptic rendering method for unsegmented images from various modalities (CT, EBT, MRI, Doppler ultrasound) was developed based on the haptic volume rendering algorithm described by Avila. Additionally, this algorithm is coupled with the Heidelberg Raytracing Model to get coherent perceptions (what you see is what you feel). Virtual elements, such as resection planes, which are necessary for a surgical planning system are described as OpenGL primitives. For that, a hybrid rendering approach was introduced combining volume and surface rendering.

Index Terms haptic rendering, surgical planning, segmentation

1 Introduction

Developing better tools for surgical planning is important to improve the quality of operations. In the field of brain surgery it is common to use machines to compute the best access to the operation area. In other surgical domains, finding the best surgical strategy depends more on the physician‘s experience. In this paper, we will describe some scenarios where haptic rendering can support the planning process in liver surgery to resect tumors.

2 Background

The resection of liver tumors is planned based on information about the individual liver anatomy. The data processing consists of three main steps [Glombitza 98]:

- Interactive classification of liver parenchyma, vessel trees and tumor
- Segmentation of liver segments by means of the preprocessed vessel trees
- Calculation of the parenchyma mass which will be available after resection

2.1 Interactive Classification

Currently, classification of different tissues in medical images is performed using VolMes [Demiris 98]. This tool, developed in our division, provides several interactive algorithms for region growing and correction to mis-classifications. It takes a skilled user about 1 minute to classify the liver parenchyma, the vessel trees and the tumor in a single CT image. The data size is about 256x256x180 voxel which results in an overall classification time of 3 hours. Up to now, no automatic classification algorithms is known that fulfills the requirements regarding accuracy. For that, the first aim using the PHANToM was to speed up the interactive classification process.

2.2 Liver Segmentation

The segmentation of liver segments (see fig. 1) is based on the information derived from the classified vessel tree. In spite of interactive classification, the vessel tree may be incorrect in terms of missing or wrong connections due to the limited resolution of the CT scanner and variances when absorbing the contrast liquid. These errors have also to be corrected manually.

Planes between liver segments are computed after correcting the vessel tree. These planes can be further manipulated. To control the automatic determination of the segments, the user (physician) can adjust them afterwards.

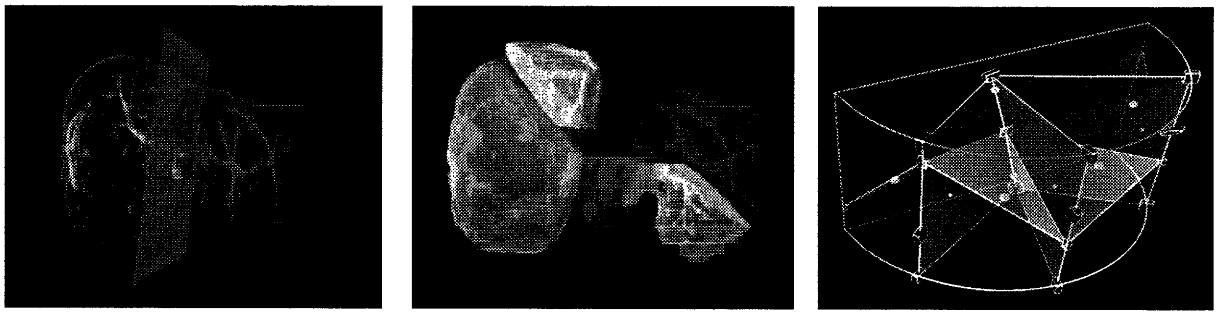

Figure 1: (left) 3D-reconstruction of a human liver including vessel tree
(middle) segment model
(right) OpenGL model of cut planes and landmarks (white spheres)

3 System Design

Beside the scenario described above, haptic interaction can also be useful in other surgical planning tasks. To achieve this, the primary design goal is to integrate haptic rendering in our image processing environment. This environment consists of a client/server architecture as described in [Mayer]. An image processing server holds the volume data during the whole processing stage and performs all algorithms on them. On request the client receives 2D image for displaying. These requested images can either be arbitrary slices from the original volume or 3D reconstructions. The reconstructions are computed using the Heidelberg Raytracing Model.

Connecting the PHANToM directly to the server was the only way to integrate it in our environment. Duplicating the volume images on the client leads to problems with procedures which will manipulate the data. A new requirement of the planning tool was the handling of virtual elements such as cut planes. To do so, they had to be integrated in the image processing server. On client side, the virtual elements exist as corresponding OpenGL primitives. To display a hybrid scene, the volume visualization and OpenGL primitives are rendered independently. The client has to combine both images using a z-buffer-merging.

3.1 Haptic Rendering

The haptic volume rendering is based on the gradient magnitude segmentation method described by [Avila 96]. Because the algorithm operates on unsegmented data, only grayvalues are considered to calculate force responses. All parameters of the rendering algorithm can be adjusted to support various images from different modalities. The force model is not intended to give a realistic feeling with this algorithm, but the user should distinguish different tissues and the transitions between them. These requirements are fulfilled with the simplified algorithm.

The virtual elements were surface rendered using the mass-spring model. The forces from both haptic rendering techniques were combined as described in equation (1). The weighting factor a can be adjusted depending on the users needs.

$$\vec{F}_{result} = a\vec{F}_{volume} + (1-a)\vec{F}_{surface} \qquad \text{(eq. 1)}$$

3.2 Displaying

Our experience in visualization of medical images showed that shadows are an important depth-clue when observing 3D-reconstructions. This led to the development of the Heidelberg Raytracing Model [Meinzer 91] which employs two light sources. Virtual elements, as the pointer of the PHANToM, are rendered in the surgical planning tool using the same lighting model as the raytracer. The OpenGL rendered primitives throws shadows on the raytraced objects. This allows the user to determine the pointer position relative to the object without wearing stereo glasses.

The mapping of density-grayvalues is used for both the Heidelberg Raytracing Model and the haptic rendering to establish a coherent perception (what you see is what you feel). The user can change this mapping interactively.

3.3 Liver Segmentation

To achieve a remarkable speedup when classifying volume images, the process has to be done in 3D. Until now, no 3D classification algorithm produced any usable result. Giving the classification algorithm some points on the surface of the object will improve these results significantly [Makabe 98]. We use the PHANToM to construct such contour points around the objects to classify. The force generated on the transition between two objects makes this method fast and accurate.

The haptic feedback also enables the user to navigate precisely through the vessel tree. This allows a correct cutting of wrongly connected vessels as well as connecting them.

All landmarks used to define the planes between segments are situated inside the vessel tree. As in the correction phase, the PHANToM makes a fast and correct navigation in 3D possible. Seeing the whole vessel tree in the 3D reconstruction allows to set all 10 landmarks from some viewpoints only. This replaces the time consuming search for the „best slice“ where to set each landmark.

The calculated planes are a suggestion how the liver may be surgically treated. The physicians should have always the opportunity to change it for further planning. For that, it is possible to change the landmarks and move the planes in all directions.

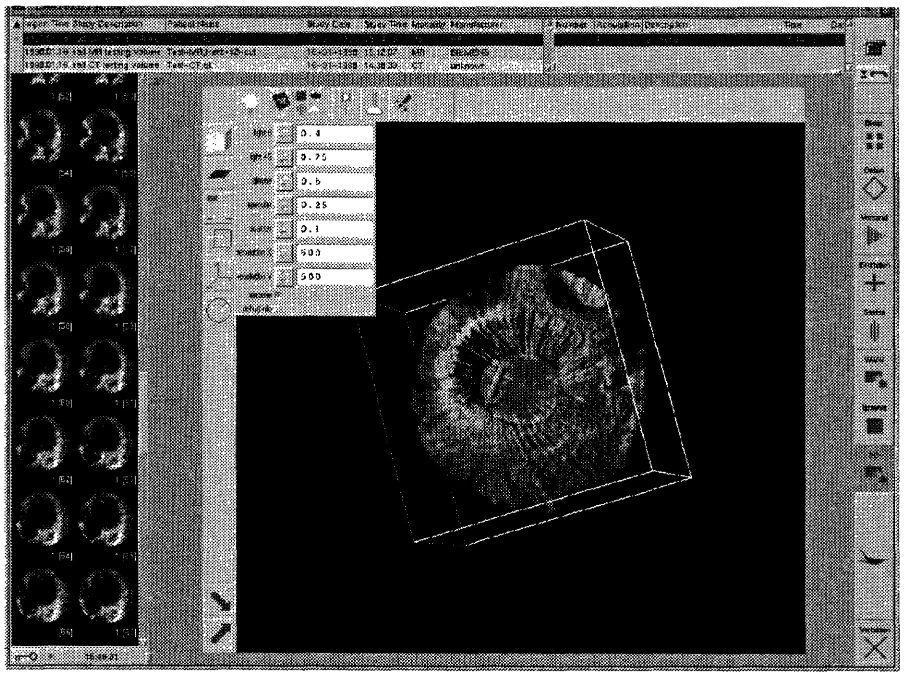

Figure 2: Teleradiology system Chili with 3D-visualization PlugIn

4 Current status

Most of the described functionality of the surgical planning system was developed independently and is implemented in several prototypes. Currently, these algorithms are integrated as a PlugIn [Evers 98] for the teleradiology system Chili (see fig. 2). Since image transfer, management and visualization is covered by this host system, developments can be concentrated on interactive visualization and segmentation in combination with haptic rendering.

5 Acknowledgements

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Rapid Rendering of "Tool – Tissue" Interactions in Surgical Simulations : Thin Walled Membrane Models

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Introduction

This paper presents a novel approach for physically based, real-time rendering of interactions between surgical tools and soft tissues for surgical simulations in multimodal virtual environments (VEs). Such VE systems require graphical rendering of organ motion and deformation together with haptic rendering of tool-tissue interaction forces (Basdogan, *et. al.*, 1998). Since these systems are aimed at training medical personnel, the sensory displays need to be realistic, requiring fast rendering of physically based models. Accurate analysis of tool-tissue mechanics is computationally very intensive due to inherent complexities of the governing partial differential equations and the nonlinearities resulting from large deformations and material behavior (De *et. al.*, 1998). Therefore, optimal choice of organ models with respect to computational speed and accuracy is crucial. We propose here models and algorithms for physically based rapid graphical and haptic rendering, especially those encountered during palpation, piercing or incision of soft tissues.

Thin Walled Membrane Models

The real world is three dimensional and this results in considerable computational burdens when it comes to modeling the objects we see around us. Moreover, if we consider dynamics, the fourth dimension of time adds to the complexity. Since we do not have the computational resources to solve for the behavior of all the material components that constitute the object, we perform some kind of discretization, be it in terms of a mesh or in terms of discrete, lumped-parameter particles. Increased dimensionality of the problem results in larger matrices and the solution cost goes up roughly as the cube of the number of unknowns. But haptic and visual interaction with three dimensional bodies are primarily superficial. While touching an object through a tool, we *see* the surface deforming under pressure and *feel* the net force due to the traction distribution at the area of contact between the tool and the object. Hence, if by some means, we could reflect the properties of the material constituents "inside" the solid to its surface, the computational burden could be reduced significantly. This is the basic idea behind the approach developed in this paper.

We view volumetric solid objects as being represented by "thin-walled" structures for the computation of surface deformations and interaction forces. Thin walled structures are found all around us. The simplest example is a balloon. It is a thin walled membrane filled (when inflated) with a gas. A more complex example of a thin walled structure is an auto-body or the fuselage of an aircraft. The important point is that such structures are common and we have efficient techniques for solving their behavior. The novelty of our approach is that we model general three dimensional deformable bodies as "thin-walled" structures so far as visual and haptic interaction with them are concerned.

A wide class of compliant organs like the stomach, spleen, etc., may be modeled as membranes enclosing a fluid, much like "water-beds" (Srinivasan, 1989). The degree of compressibility of the organ can be controlled by defining an appropriate Bulk Modulus for the fluid inside. When bending stiffnesses are higher, the model can be extended by replacing the membrane with a shell structure with or without fluid inside. The "surface model" of the organ, used to define its geometry in computer graphics algorithms, is adopted as the surface of the thin-walled structure. But, unlike the "surface models", we endow the organ surface with a thickness that can be variable across the surface. Finite element analysis is performed by discretizing the membrane with the same triangular elements used in representing the organ geometry graphically (see Fig 1). A total Lagrangian formulation (Bathe, 1996) is adopted to obtain the incremental equations of motion, thereby transforming the nonlinear problem into a sequence of simpler linear problems. The effect of the internal fluid pressure manifests itself in two ways. First, it adds extra terms to the tangent stiffness matrix and secondly, it shows up as an applied force term in the equilibrium equations. The choice of simple triangular elements results in closed form computation of the global tangent stiffness matrices (non-symmetric), resulting in a substantially accelerated computational procedure.

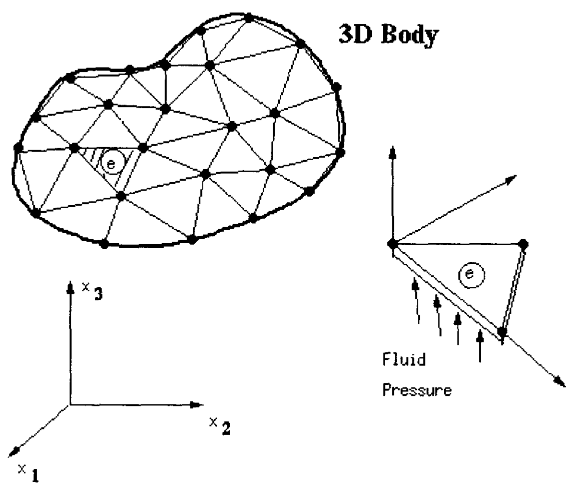

Figure 1 A general three dimensional body is modeled as a membrane filled with a fluid and discretized with linear triangular elements. One such triangular element is also shown in its local coordinates. The fluid pressure acts on one face of the triangle.

Results

One of the major strengths of this modeling scheme is that it is capable of simulating the nonlinear force-displacement behavior observed in actual *in vivo* experiments performed on biological tissues. To illustrate this point, we have shown in Figure 2 the force-displacement results (dashed lines) obtained when a human fingerpad is indented by a point load (Srinivasan *et. al.*, 1998). The fingerpad has been modeled as a semicylindrical membrane in plane strain, enclosing an incompressible fluid. The solid line indicates the result of the simulation.

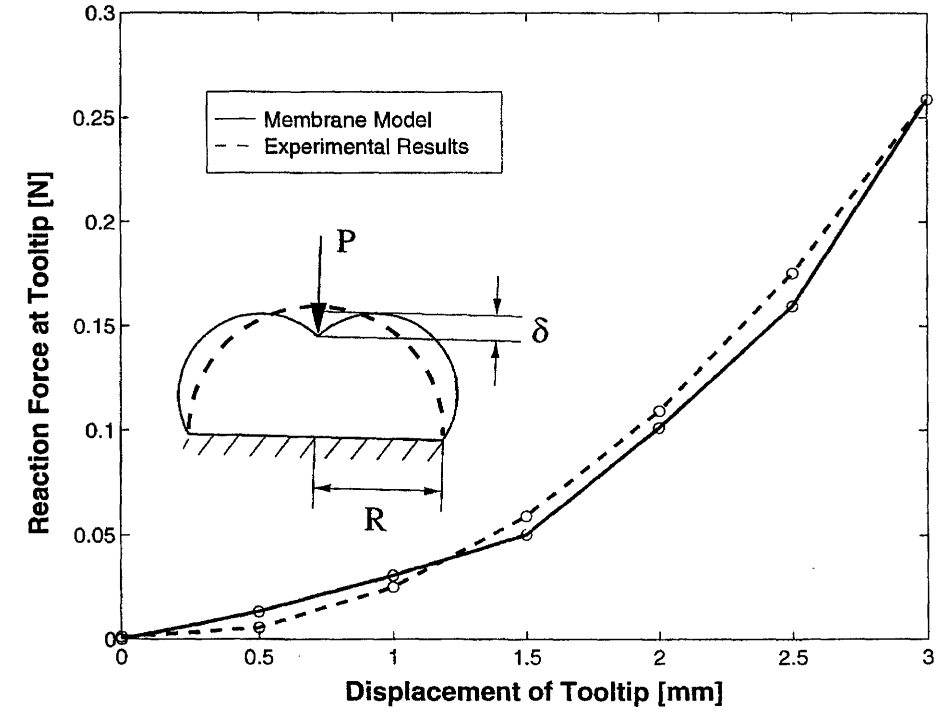

Figure 2 This figure shows the match in force-displacement response between *in vivo* experiments performed on the human fingerpad by a point load and numerical simulations performed on a fluid filled membrane model of the fingerpad. The dashed curve represents the force (N) versus displacement (mm) response of a human fingerpad under steady state conditions when indented by a point load to various depths of indentation. The fingerpad is modeled as a semicylindrical membrane of radius R = 10 mm, filled with an incompressible fluid and subjected to the same depths of indentation , δ, by a pointed tooltip. The solid curve shows the corresponding force-displacement relationship at the tooltip obtained from the model.

Conclusions

In this paper we have presented a new way of modeling soft tissue behavior during surgical simulations. The novelty lies in modeling 3D continua as thin walled membrane structures filled with fluid. These simple models reduce the dimensionality of the problem from 3D to 2D and are therefore computationally extremely efficient. Moreover, they have the power to predict the non-linear force-displacement response as well as the surface deformation profiles as observed in *in vivo* experimental data on soft tissues. Among other benefits of using this approach are the flexibility to model inhomogeneous and viscoelastic tissue behavior, ability to deal with realistic three-dimensional organs with relatively low computational overheads and a unified approach to haptic and graphical rendering of general deformable media.

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ASSESSMENT AND VALIDATION OF A FORCE FEEDBACK VIRTUAL REALITY BASED SURGICAL SIMULATOR

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BACKGROUND:

The goal of surgery residency training programs is the production of a "skilled, safe, technically adept surgeon with keen judgment, dedicated to the welfare of his or her patient" (Aufses, 1989). Surgical education and training is a lengthy, expensive process based upon the apprenticeship model. Trainees (surgical residents) learn technical skill by the "see one, do one, teach one" method. This practice is not without risk to the patient, and often leads to increased operating room time, a higher complication rate, and greater cost (Krummel, 1996). The development, assessment, and validation of a virtual reality based, force feedback surgical simulator has been undertaken to counter this educational model.

The novel concept of virtual reality (VR) based simulation in surgical training is derived from the airline industry, where the use of simulators is well established. Full scale simulation is fully integrated into commercial and combat pilot training at all levels, and has been shown to effectively train pilots for all manner of flight conditions (Rolfe, 1986).

Surgical simulators for education and training are not commonly used due to the early developmental stage of many of the applications, the relatively high cost of building or acquiring systems, and the lack of strong data confirming their validity. All of these factors must be addressed before widespread adoption of surgical simulators as training tools takes place. However, the use of virtual reality and simulation in surgical training is gaining credibility (Krummel, 1998). Currently, information on optimal training programs (learning curves) for surgical trainers is not readily available. In our laboratory, we are studying learning curves generated from various training protocols designed for a force feedback surgical simulator.

Surgical skill is difficult to measure. Attempts at evaluation have included skill laboratories with video monitoring, self-instruction modules, and physical models (Barnes, 1989). Other assessment criteria depend upon subjective faculty evaluations, or raw scores generated from paper and pencil examinations (Polk, 1983). Few objective standards, if any, exist. We used a VR based, force feedback surgical simulator to determine if objective documentation of early skill acquisition were possible. Baseline skill data were collected on beginning surgery residents in an attempt to measure skill in a single surgical task, and to discover the extent to which, if any, psychomotor learning took place.

METHODS:

The system that was used is centered upon an innovative, double-armed, force feedback surgical simulator developed in collaboration between the Penn State College of Medicine Department of Surgery and Boston Dynamics, Inc (Cambridge, MA). A surgical needle driver and forceps are attached to two Phantom™ haptic devices (Sensable Technologies, Inc., Cambridge, MA). A desktop computer is used to control the haptic element, while a separate computer provides the graphics component. A dedicated software program measures six variables (below) of operator performance.

Eleven beginning surgery residents underwent a standardized training program on the surgical trainer. Each participant spent fifteen minutes per day (three days total, days two and three non-consecutive) driving a simulated needle through a target overlying a simulated blood vessel with photo-realistic graphics and rudimentary tissue properties. Data were collected on time on task, accuracy, peak force applied, tissue damage, surface damage, and angle error. An overall score was derived, and the overall scores of days one, two, and three were compared using Fisher's Exact Probability Test. A *p* value of less than 0.05 was considered significant.

A second pilot study involving five surgical novices was undertaken to determine the amount of training required to reach a skill level "plateau." Each subject's task in the virtual environment was, as above, to complete multiple passes of a simulated needle through a target on a simulated blood vessel. Data were collected on, and an overall score was generated from, the six parameters mentioned above. This was done until the overall scores leveled off. Twenty minutes were allotted per session (one session per day, weekends excluded).

RESULTS:

The resident's overall scores on day one (39.78 ± 12.36, mean ± standard deviation) increased on day two (49.12 ± 16.75), with a further increase noted on day three (56.31 ± 12.33). The daily increases were not statistically significant ($p=0.085$ and 1.0 respectively). However, day three scores were significantly higher than day one ($p=0.0009$). Four subjects improved their overall score by more than 10 points from day one to day two, and four from day two to day three.

The group consisting of surgical novices underwent daily sessions (range 13-17) over a 24 day period. On average, the overall score began to plateau after 7 to 11 sessions. Group average day one scores of 25.2 ± 18.5 (mean ± standard deviation) improved to 73.4 ± 7.1 by the end of the study ($p<0.05$).

DISCUSSION:

Using this methodology and instrumentation, we were able to collect baseline skill level data on beginning surgical trainees, and demonstrate that learning took place by showing improved psychomotor performance. The second study showed that multiple, discrete sessions contributed to attaining a training plateau. Session-free days did not appear to adversely effect the learning process.

These findings complement the work of O'Toole and others, whom, while testing a similar surgical simulator, found that practicing surgeons outperformed medical students on identical tasks, and concluded that the simulator "may be useful in quantifying surgical skill" (O'Toole, 1997).

Problems with the system as presently configured include accurately defining and quantifying concepts such as tissue damage, peak force, and surface damage. Currently, there are no reliable standards for measuring these behaviors in living tissue. Correlation of raw scores with expert surgeon evaluation is needed to further refine the importance (weighting) given to each of the six individual parameters.

We conclude that this VR based, force feedback surgical simulator may prove useful in measuring, in an objective fashion, psychomotor learning. In addition, training on this surgical simulator does lead to significant score improvement in six performance metrics, with eventual learning curve plateau.

Acknowledgments:

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Soil Simulation with a PHANToM

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Abstract

A method for haptically simulating soil is presented. The simulation is created by using a physical model of the dynamics of a rigid planar surface moving through a particulate system to calculate appropriate force output commands to the haptic interface. The technique was applied using a PHANToM haptic interface device with good initial results.

Introduction

This paper presents a technique for simulating haptic interactions with virtual soil. The approach to creating the simulation is based on physically modeling the forces generated when a flat, straight, and rectangular plow blade moves through a soil with a given set of properties. A simple example of the kind of interaction under discussion is pushing beach sand around with a spatula or shovel. The mechanical model used to drive the simulation is a modification of one presented in original research conducted by McKyes and Ali [McKyes]. In the original model, the forces on a plowing surface may be calculated based upon the geometry of the plowing surface and certain soil properties. The geometric specifics of the plow blade that are included in the McKyes and Ali model are its width, depth of penetration into the soil, and orientation of the blade surface with respect to the direction of motion through the soil. The three soil properties included in the model are density, cohesion, and angle of internal friction.

Both the Viking and Pathfinder Mars exploration missions also used the McKyes and Ali model as the basis for a method of roughly determining Martian soil properties [Moore] [Rover Team]. It was the goal of our research to provide a means to simulate soil properties in a scientifically meaningful manner in order to provide researchers interested in soil properties with a tool for gaining an intuitive understanding of remotely sensed soil data.

Dynamic Model

The basis of the model is to assume that at any instant as a plow moves through the soil a discrete volume of material disturbed. The magnitude and dimensions of this volume can be determined by calculating a shear failure boundary based on mechanical properties of the soil, the geometry of the plow blade, and the angle of attack. From this volume the forces acting on the blade can be computed based on the density, angle of internal friction, and cohesion of the soil, as well as any load on the surface of the soil and friction between the plow blade and soil. The model neglects inertial forces assuming they are relatively insignificant.

Dry, sandy soils may be considered cohesionless and shear strength arises from the friction between particles. Cohesive shear strength is derived from ionic bonding between soil particles and has been found to be the dominant source of shear strength in clay-based soils [Liu p235-236].

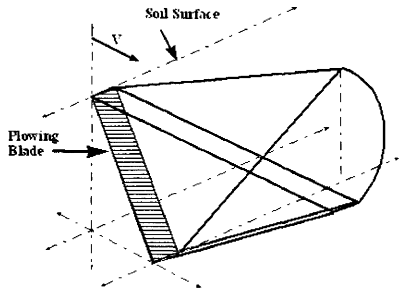

Figure 1. Disturbed Soil Volume

Figure 1 illustrates the basic idea of the McKyes and Ali construct. It consists of a triangular center volume bordered by conic sections on either side (in figure 1 one side has been omitted for clarity). From these sections we can compute the forces on the blade by computing the force factors from the separate volume sections and summing the results. Figure 2 shows the model for the center section of the disturbed soil volume.

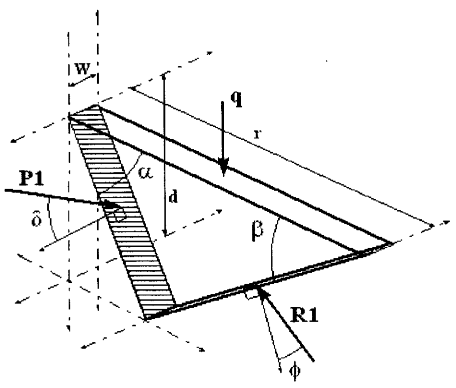

Figure 2. Model for Center Volume

The force generated on the plow blade from this section is derived from a force balance equation. The variables and constants involved are listed below and all variables are in SI units.

$w \equiv$	Width of Blade (m).
$d \equiv$	Depth of Blade Penatration Into Soil (m).
$P1 \equiv$	Magnitude of Force Blade Exerts On Soil (N).
$R1 \equiv$	Magnitude of Force Exerted on Soil Shear Failure Plane by Undisturbed Soil (N).
$q \equiv$	Load on Surface (N / m^2).
$r \equiv$	Radius of Failure Zone At Surface (m).
$\delta \equiv$	Soil / Metal Interface Friction Angle (Rad).
$\phi \equiv$	Soil Internal Friction Angle (Rad).
$\alpha \equiv$	Angle of Plow Blade From Horizontal (Rad).
$\beta \equiv$	Angle of Soil Shear Failure Plane (Rad).
$c \equiv$	Cohesion of Soil (N / m^2).
$\gamma \equiv$	Bulk Density of Soil (N / m^3).

$\theta_1 = \alpha + \delta \qquad \theta_2 = \beta + \phi$

The forces are resolved into their horizontal and vertical components in the force balance equations and then combined to solve for the force P1 that the blade is exerting on the soil volume. The horizontal force balance equation may be written

$$P1 \sin(\theta_1) - R1 \sin(\theta_2) = \frac{c\,d\,w \cos\beta}{\sin\beta}$$

Equation 1.

where the right hand side of the equation represents force from the cohesion of the soil. Similarly, the vertical forces can be represented by the equation

$$P1 \cos\theta_1 + R1 \cos\theta_2 = \frac{\gamma\,d\,r\,w}{2} + c\,w\,d + q\,r\,w$$

Equation 2.

where the right hand terms, read from left to right, represent forces from the density of the soil, cohesion of the soil, and surcharge load on the surface of the soil. Now, solving for R1 in terms of P1 in equation 1 and substituting the result into equation 2 we finally solve for P1and find

$$P1 = \frac{w\left[\,0.5\gamma d r + c\,d\left[1 + \cot\beta \cot\theta_2\,\right] + q\,r\right]}{\cos\theta_1 + \sin\theta_1 \cot\theta_2}$$

Equation 3.

which is the solution to the magnitude of the component of force the plowing blade must be exerting on the displaced soil volume to balance the forces on the center section. This force magnitude is the resolved into its horizontal and vertical components,

$$\mathbf{F}_{P1} = P1\langle \sin\theta_1, \cos\theta_1 \rangle$$

Equation 4.

resulting in a two dimensional force vector.

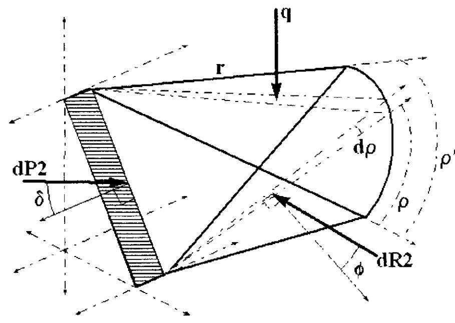

Figure 3. Model For Side Volume

Figure 3 shows the model used to compute forces on the plowing blade from a side wedge. The analysis is based on integrating forces from differential volume elements dρ over the total angle ρ' subtended by the section. Pausing then to properly define the new variables,

$d\rho \equiv$ Differential volume element (m^3).

$\rho \equiv$ Angular displacement of dρ (Rad).

$\rho' \equiv$ Total angle subtended by section (Rad).

we approach the problem as before, computing the force balance equation for each differential element. First, the force balance in the horizontal direction

$$dP2 \sin\theta_1 - dR2 \sin\theta_2 = \frac{c\, r\, d\, d\rho \cos\beta}{2 \sin\beta}$$

Equation 5.

where the term on the right hand side of the equation is the force arising due to the cohesion of the soil. The vertical forces sum as follows

$$dP2 \cos\theta_1 + dR2 \cos\theta_2 = \frac{1}{6}\gamma\, d\, r^2\, d\rho + \frac{c\, d\, r\, d\rho}{2} + \frac{1}{2} q\, r^2\, d\rho$$

Equation 6.

where the right hand terms, from left to right, are forces due to the soil's bulk density, its cohesion, and surcharge load on the surface. Proceeding as before we solve for dR2 in terms of dP2 in equation 5 to eliminate the dR2 term, and substitute the result into equation 6 in place of dR2. Solving for dP2 we find

$$dP2 = \frac{\left[\frac{1}{6}\gamma\, d\, r^2 + \frac{1}{2} c\, r\, d\left[1 + \cot\beta \cot\theta_2\right] + \frac{1}{2} q\, r^2\right] d\rho}{\cos\theta_1 + \sin\theta_1 \cot\theta_2}$$

Equation 7.

as the solution to the magnitude of the force that the blade is exerting on the differential soil volume dρ. This resolves into the horizontal and vertical components shown in equation 8.

$$dH_{P2} = dP2 \sin\theta_1 \cos\rho$$
$$dV_{P2} = dP2 \cos\theta_1$$

Equation 8.

These force components are then integrated over the total angle subtended by the wedge ρ' to compute the total force the plow blade exerts on the side conic section of disturbed soil.

$$H2 = \int_0^{\rho'} dH2 = \frac{\left[\frac{1}{6}\gamma\, d\, r^2 + \frac{1}{2} c\, r\, d\left[1 + \cot\beta \cot\theta_2\right] + \frac{1}{2} q\, r^2\right] \sin\theta_1 \sin\rho'}{\cos\theta_1 + \sin\theta_1 \cot\theta_2}$$
$$V2 = \int_0^{\rho'} dV2 = \frac{\left[\frac{1}{6}\gamma\, d\, r^2 + \frac{1}{2} c\, r\, d\left[1 + \cot\beta \cot\theta_2\right] + \frac{1}{2} q\, r^2\right] \cos\theta_1\, \rho'}{\cos\theta_1 + \sin\theta_1 \cot\theta_2}$$
$$\mathbf{F}_{P2} = \langle H2, V2 \rangle$$

Equation 9.

We now have a solution to the problem of computing force on the blade of a plow as it moves through soil of a given bulk density and cohesion with a given internal friction angle. The force on the plow then is the vector sum in equation 10 where F_{P2} is doubled to account for the second conic section of soil.

$$\mathbf{F} = -(F_{P1} + 2 * F_{P2})$$

Equation 10.

Implementation

In the implementation of the soil simulator values were taken from a source text on soil mechanics [Liu p. 411] to match the properties of cohesion *c*, bulk density *γ*, and angle of internal friction *ϕ* for various sandy soils. The soil types that the PHANToM and dynamic model are suited to mimicking are limited to loosely packed, medium-to-fine grained sands, silts, and dry clays. High cohesion factors require forces too large for the PHANToM to render and large grain sizes, relative to the plow-bladed size, break down the validity of the model.

In a departure from the McKyes model a failure plane angle *β* is chosen based upon the Rankine theory for passive lateral earth pressures [Liu p.401]. The McKyes and Ali plowing theory model selects a failure plane angle *β* that minimizes the horizontal force term arising from the soil density [McKyes p.48]. This minimization process is too costly in terms of processing time for a control loop and so this simplification was made. The Rankine model provides a method for computing forces on earth bearing walls that are moving relative to the soil.

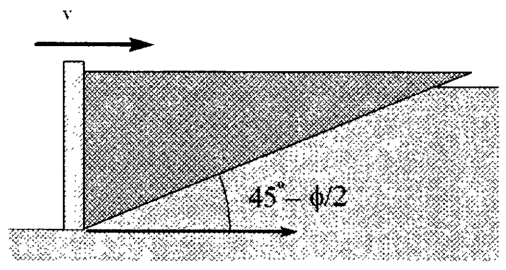

Figure 4. Rankine Model Failure Plane Angle

Figure 4 shows the predicted failure plane angle as an earth retaining wall moves toward the soil mass.

In order to give the simulation a more realistic feel the friction angle *ϕ* and the failure plane angle *β* are perturbed with the Gaussian random distribution algorithm. As stated above base values for these factors are taken from civil engineering sources such as [Liu] and [Lambe] and used as the mean values, while the standard deviation values used are found through trial and error to give the most natural feeling results.

The two-dimensional force vectors calculated above are then applied in the instantaneous direction of motion. This is approximated by first finding the vector difference between the current and last positions of the end-effector in virtual space. The projection of this vector into the horizontal plane is then normalized to get a unit vector in the current direction of motion in the horizontal plane. Force output to the haptic device can then be applied in the calculated direction.

Results

The soil simulation results are encouraging. A reasonably convincing simulation of probe/soil interaction is created using the methods described. The soil parameters of density, and internal friction angle may be varied to achieve palpably different feeling soils. Cohesion needs to be very large (hundereds to thousands of Kilo-Pascals) to achieve perceptible changes in the soil behavior and was left at or near zero for most simulations. The validity of this choice is supported in the soil mechanics literature [Liu pp. 235-242] which contains statements to the effect that dry sandy soils are virtually cohesionless. Cohesion becomes a dominant factor when examining the shear strength of clay based soils.

The plow blade dimensions were also changed to observe the effect on the simulated soil interaction and the results were as would be intuitively expected. Specifying a wider blade in the model causes more resistance to movement while a narrow blade achieves the opposite effect.

Experiments were conducted to observe the effect of velocity on the impedance experienced by a real plow blade moving through real sand to verify the validity of the model's velocity independence. Impedance was found to be independent of the angular velocity of the PHANToM for a set of velocities within a range of values tested from 0.25 to 1.5 Rad/sec. A more detailed discussion of these experiments appears in [Green Chpt 4.].

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"Nearest Neighbor" Approach to Haptic Collision Detection

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Some form of collision detection is usually central to any haptic simulation. Typically, a user moves some device though physical space, and motors are turned on appropriately to give the sensation of contact with some virtual object. So the "collision detection" required is between a physical probe and a presumed virtual object. The situation seems simpler in haptics than in computer graphics, in the former we need only consider possible collisions between a single probe point and the virtual environment, whereas in the latter one often considers possible collisions between many differently shaped objects. Diego Ruspini [1] has used a "bubble tree" approach to haptic collision detection, one searches down a pre-constructed tree of finer and finer resolutions to check for collisions of the probe point with the virtual object. This method in fact works just fine, but one might criticize the fact that one throws away the position of the probe at each time step, and has to begin the tree search anew. In fact, the probe point moves smoothly and, usually, slowly, on the computer's time scale. One should be able to use the information of the prior probe position to speed up the search. A method which will clearly work for convex objects is suggested by the figure below:

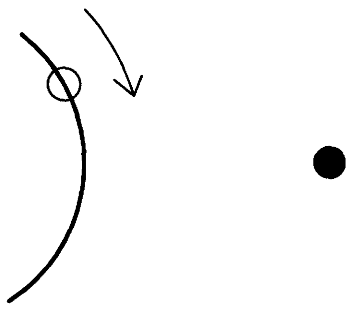


Fig. 1

One imagines a point charge free to run around on the surface which is attracted towards the probe point. For a convex shape, the moving surface charge will strive to be as close as possible to the probe point, and is guaranteed to be directly under the probe point if it should hit the surface. So, to do collision detection, one need only compute the distance between the probe point and the cruising surface point, and turn on the motors when this distance becomes zero. This is pretty obvious, and in fact is a simple case of the "Lin-Canny" algorithm for performing collision detection between any number of convex objects[2].

Surfaces are represented in the computer by vertices and edges, typically forming a net of triangles, so the strategy of the haptic nearest-neighbor collision detection would be to find the three vertices closest to the probe point, and check for collision with the triangle so formed. Finding the vertex nearest the probe point is easy, if one has an idea of where it was at an earlier time step. In advance one constructs a look-up table of the neighbors of each vertex, and at each time step one computes the distance of each neighbor of the old surfaceposition to the probe position, and hops the new surface position to whichever neighbor vertex is now closest. Because only a table lookup is required, and a sum of three squares computed for relative distances, this process is extremely fast. In fact basically this idea was presented by Chih-Hao Ho, at the recent Phantom user's group meeting, for the case when a probe is kept in contact with a virtual object[3]. This is not collision detection per se, but the same sort of nearest-neighbor data structures were used to quickly keep track of the probe position as it slides along the surface.

The fly in the ointment for haptic collision detection is, what about the case of non-convex objects? One can readily imagine an object with hills and valleys, which could trap the moving surface point in a local minimum, so that it would not actually be at the closest point on the surface to the probe point. The Lin-Canny algorithm in fact fails for non-convex objects.

The purpose of this note is to point out the surprising fact that this nearest-neighbor attraction algorithm for collision detection between a closed surface and a probe point will still work for a rather wide class of concave shapes. Further, that whether or not this algorithm will work can be the basis for an interesting and perhaps novel geometrical classification of solid shapes. So let's present the following

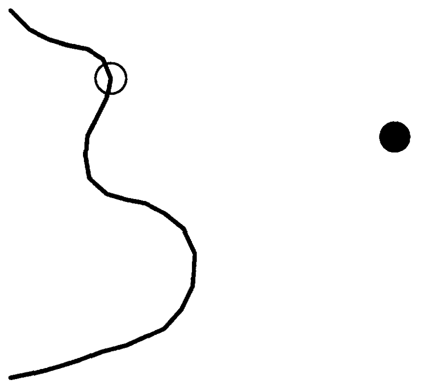
Theorem:

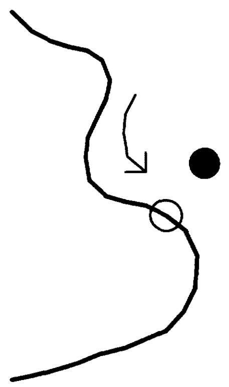
A point constrained to a smooth closed surface, which moves to be as close as possible to an external probe point, will always be directly under the probe point should it touch the surface, no matter what the path of the probe point,
if

A: No normal to the smooth closed surface re-intersects the surface, and
B: Certain special initial positions of the surface point are avoided.

A few diagrams of the two-dimensional case will illustrate the ideas, and indicate a sketch of a proof.

2a





2b

In figure 2a above the surface point is trapped in a local distance minimum which is clearly not the global minimum distance from the probe point to the surface. But note what happens when the probe point approaches the surface. (Fig 2b) If the concavity is shallow enough, the local distance minimum will disappear, and the surface point will slide under the probe point. The condition for a "shallow enough" concavity is exactly that no normal re-intersects the curve, see fig. 3 below. Note that this condition requires a pretty extreme concavity, if a normal re-intersects, the surface point can be pulled in the direction of the arrow in the figure, away from the probe point, as measured along the surface.

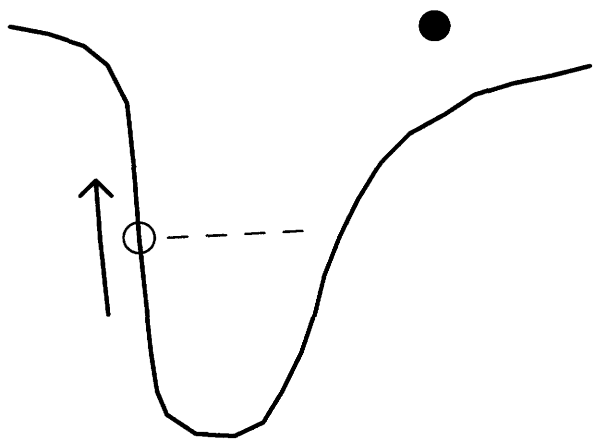


Fig. 3

A careful proof requires technique beyond that which the writer possesses, the writer hopes that a mathematician might find these arguments interesting enough to clarify. But informally, the proof of the theorem seems almost self-evident. If the external probe touches the object without the surface point being present, the moving point must be hung up on some lobe of the object, at a local gradient minimum, as in Fig.3. By definition, the ray from the surface point to the probe must be normal to the surface. Thus, for nearest-neighbor to fail, normal re-intersection is necessary.

The initial condition caveat is required for the situation when the surface point is trapped in a dimple behind the object, and the probe is in front of the object, the surface point won't be there to meet the probe point when it touches the front surface. But note that this configuration is unstable, once the surface point is on the front surface, the special initial configuration cannot be re-established, no matter what the path of the probe point. Again, an informal proof is not too difficult, we have to consider appearance and disappearance of basins of attraction as the probe point is moved around the surface. We have to show that a) a basin never appears directly under the surface point, and b) the surface point never crosses a basin boundary. I think both of these are clear, a) is true because basins can only appear "over the horizon" if the normal condition is obeyed, and b) is true by definition of basin boundary.

The above arguments work for closed surfaces in three dimensions, except that the no re-intersecting normals condition is sufficient but not necessary for freely sliding surface points. An example is a simple donut, which certainly has re-intersecting normals, but no trapping regions. Note that the surface areas with re-intersecting normals are negative curvature saddles, the surface point, while trapped in one surface direction, can slide toward the probe point along the other direction. The complete necessary condition is the following. For "bumps", i.e. two positive radii of curvature, no re-intersecting normals is a necessary condition. A normal emanating from a "dimple", with two negative radii of curvature, must not re-intersect within a distance equal to the smaller of the two radii in absolute value. For the saddle case, the surface point will slide away from the normal for a distance out along the normal greater than the absolute value of the negative radius of curvature.

Comments:

The presumed attraction between the probe and the surface point can be thought of as a gradient field centered on the probe, the projection of this gradient onto the surface produces a vector field on the surface, which the surface point follows as it strives to be as close as possible to the probe. This sort of construction falls under the purview of "Morse theory". A clear exposition of Morse theory, in fact the only exposition which the writer with his limited background found accessible, is contained in David J. Kreigman's work entitled "Let them fall where they may" [4]. In this work Kreigman considers the "capture regions" which lead to one or another of the "stable poses" of a solid shape on a smooth flat table. This problem has a two-dimensional configuration space, corresponding to the two-dimensional set of possible orientations of the solid shape. As far as I can see, the topological possibilities Kriegman considers are identical to those encountered in my problem in the case where the probe point is infinitely far away, this also posseses a two-dimensional parameter space. The full problem has a three-dimensional parameter space, as the center of force can approach the solid object. The basins of attraction of various "capture regions" can merge and/or disappear, I may or may not be the person to carry out this analysis.

Even in the absence of practical application, the normal-reintersection criterion supplies an interesting geometrical classification of smooth solid shapes into "convex", "concave", and "very concave". But for the polygonal models of a computer representation, we have to find the appropriate discrete versions of concepts such as "normal" and radius of curvature which are defined on smooth surfaces. This so far is incomplete, but the writer believes it is possible, and is trying to prove the following conjecture. Nearest-neighbor attraction collision detection will work for an arbitrary polygonal mesh, if one allows at most one non-local entry in the lookup table of each vertex. Maybe typically only a few isolated "bridges" are needed, to slide the surface point out of a region where it has become stuck. Can a scheme like this be used to extend the Lin-Canny algorithm?

I would like to thank Gavin Miller, Norman Packard, and Bill Verplank for helpful discussions.

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Adding Haptic Device to Virtual Reality Based User Interface Systems

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Abstract

Ability of haptics technology will be realized and spread with its connection to other technology like a visual simulation or network system.

LEXER RESEARCH is a Japanese company that provides a software tool 'aWORLD' that has GUI for virtual reality system for industry, education, creation or network communication.

At this time, LEXER RESEARCH has developed the aWORLD family software 'aWORLD-HAPTICS' to connect aWORLD to PHANToM device. Using this system, CAD data is ready-to-use with the PHANToM device. aWORLD-HAPTICS will make it possible to not only touch objects as well as watch objects, but also deform object with elastic mathematical deformation model.

This system can make PHANToM a general device in VR user interface, and can apply haptics technology to many fields.

Introduction

One of a purpose of this work is to investigate the haptic device activity with connection to multi-purpose visual system. Another is to investigate the optimized system architecture to connect Haptics device to 3D visualize system. Human recognition toward scene is consisted of multi modal concerned with human sensation. And virtual reality technology can be utilized as cyber space interface system. Regarding virtual reality system as user interface system, it is important that haptics sense and interaction will be supported. Haptics device will provide the impressionable reality in virtual reality scene, but there are few virtual reality systems provide such a function. On the other hand, although application fields of haptics technology will be going to spread, there are few tools to integrate the application system with haptic device.

In order to develop more effective and convenient environment of virtual reality, it is one of the way that haptics device will be added to multi-purpose visual virtual reality system. In this work, we adopted PHANToM to visual virtual reality system 'aWORLD' that has the distributed network system architecture and can indicate the ability of haptic device.

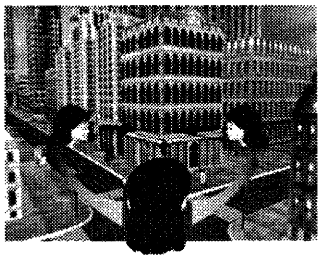
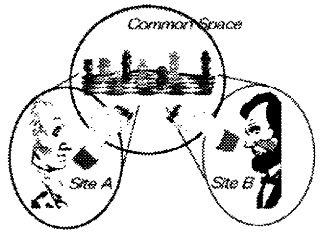



Figure 1 deTach&atTach Figure 2 Rasso View Figure3 Common Space

Vitural Reality system 'aWORLD'

LEXER RESEARCH has been investigating scene recognition and human interface technology for information system. Among these investigations, LEXER RESEARCH has developed the virtual reality system 'aWORLD' that has GUI, scene data interface and functions for virtual reality system for industry, engineering, education, creation or communication.

This system has many useful scene authoring functions as user-interface function such like a 'deTach&atTach' that works as 3D-drag&drop with mouse(Figure 1), or 'Rasso' view that makes a user view move around, approach, ascend or descend with mouse dragging toward a 3D-point that is pointed and focused by mouse. (Figure 2)

On the other hand, aWORLD has the excellent system architecture that is able to make the network distributed system for adoptive system function or system devices or user applications. (Figure 4) This system is consisted on aWNC(aWORLD Network Connection) that can be connect a graphics rendering subsystem to other subsystem with several methods. Through this architecture, aWORLD can be defined as a sensible interface system between user and intelligent systems. We call this idea, VRUI(=Virtual Reality User Interface) as user interface concept with virtual reality technology.

Additionally saying, utilizing aWORLD Network server, aWORLD will be extended to multi-user system to integrate common 3D space for collaborative creation (Figure 3)

In this project this flexible system architecture is applied in order to integrate haptics device.

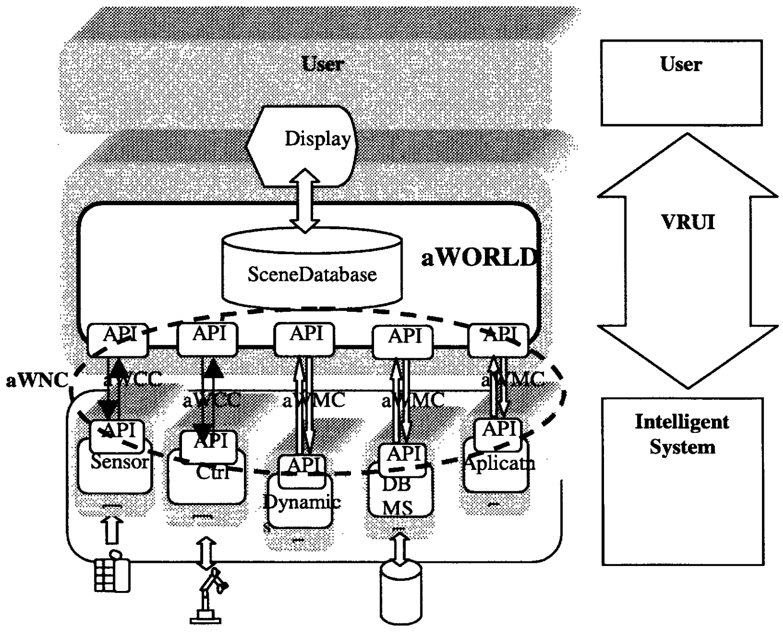


Figure 4 aWORLD Network Connection System

Connection between PHANToM to visualize subsystem

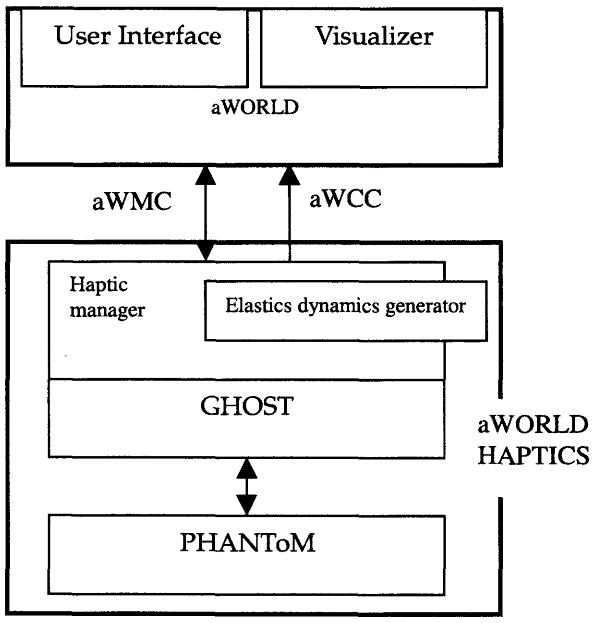


Figure 5 System Architecture

In this project, we used GHOST haptic module as haptic rendering engine. Both visual and haptic rendering process will take much cost for computer performance. It is one of way with regard to this problem to separate visual rendering process and hapic rendering process in multi processing environment. In order to do this implementation, aWORLD network connection system (aWNC) that makes the connection between graphics rendering system and haptics rendering system is adoped. aWNC provides two methods for connection between subsystems, one is to transfer channel values to another subsystem each other,(aWCC: aWORLD Channel Connection) another is to transfer messages to control another subsystem each other.(aWMC: aWORLD Message Connection) (Figure 5) This connection system works on UNIX, Windows95 and WindowsNT platform in Eathernet environment. aWCC prepares virtual channel that automatically transfer value data and keep consistency between subsystems on UDP/IP protocol. On the other hand, aWMC prepares many messages to control another system and callbacks to be controlled by other system on TCP/IP protocol. With aWNC network API which aWORLD provides, application can be built without consciousness toward network system.

In this project, visualize rendering system runs on SGI/UNIX and haptics rendering system runs on WindowsNT, because of each system having proper performance for each purpose, visualize rendering and haptics rendering. Our approach increases visual rendering rate and haptics servo rate and that makes system stability higher.

To connect subsystems each other this project developed the communication system with channel connection (aWCC) as visual pointer control corresponding to PHANToM haptics pointer and message connection (aWMC) as scene databases bi-way control that makes haptics database update from visual database update and visual database update from haptics database. Utilizing this connection system, visualize system scene control functions, for example, object data loader, object move control or material change control (include haptics material) will be automatically applied to haptics system and haptics system scene update will be automatically applied to visual system. We named this system 'aWORLD HAPTICS' for visual-haptics virtual reality system. Thus, in this project with aWNC, total system consistency is built with keeping system flexibility.

Besides, there is a limit of quantity for haptic database ability. To solve this problem, this system provides selectable data loading system to control the load of haptics rendering system. In case of material name having haptics parameter, graphics scene database transfer object data to haptics scene database. Therefore, only setting material name having haptics parameter to several objects that user needs to touch, haptics rendering load will be reduced, while all the objects will graphically displayed.

Elastic model implementation

To be useful in haptics applications, not only touching effect but also object deformation will be effective. And ability of scene manipulation will be useful too. In order to implement these functions, we append elastic module and manipulation module to 'aWORLD HAPTICS'. These modules is set in front end of 'aWORLD HAPTICS' module to visual rendering subsystem. (Figure 5)

In this work, dynamic elastic deformation function was implemented. For elastic deformation, propagation method spreading from touching point with PHANToM was applied. Data model for the propagation process is quoted from visual model in order to sustain user's controllability for deformation. It's depend on the idea that optimization will be controlled by user in unknown system performance environment. In the generation of propagation model, a connectivity between vertexes that constitutes object polygons is needed to preserve. Therefore, the connectivity of vertexes in the object is generated simultaneously with getting data from visual rendering scene database.

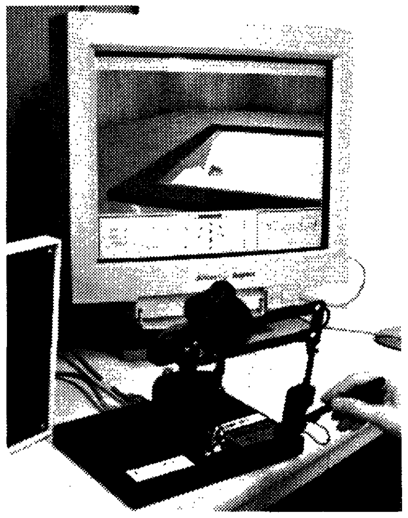
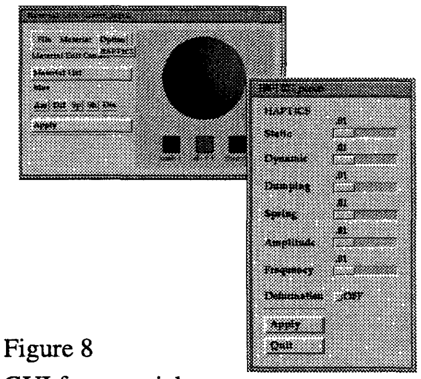


Figure 7 Trampoline model

Example

To demonstrate the use of this system, some demonstration has been made for aWORLD HAPTICS.

In this work, we tried to build a trampoline demonstration that has elastic face and hard frame. (Figure 7) With 3D CAD system, we had made frame objects and rubber face objects that have triangle mesh structure to deform like realistic pushing rubber face. If each frame is defined with a material name having haptics parameter, a haptic trampoline scene will be build only reading trampoline data file from aWORLD system menu. If user needs to change haptics material, haptics material parameter will be changed with GUI of aWORLD. (Figure 8)



HAPTICS
Static .01
Dynamic .01
Damping .01
Spring .01
Amplitude .01
Frequency .01
Deformation OFF

Figure 8
GUI for material

Conclusions

In this work, total system consistency in multi-processing environment for visual and haptics rendering processes is built with keeping system flexibility via aWNC provided with aWORLD. Thus, according to the connection of haptic device to standard virtual reality system, 3D haptic interfacing device will be a general device in VR user interface, and can be easily applied to many fields.

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5 DOF Force Feedback Using the 3 DOF Phantom and a 2 DOF Device

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ABSTRACT

This paper describes the development of a 5 active degree of freedom haptic interface intended for arthroscopic surgery simulation. Arthroscopic surgery is an increasingly common surgery for which more advanced training methods would prove very useful. The interface, a 2 DOF planar device which supplements a 3 degree of freedom device, can apply general forces and moments in all directions, except moments about the tool handle axis.

I. INTRODUCTION

Arthroscopic knee surgery, and arthroscopic and laporascopic procedures in general, is becoming more popular due to the effectiveness of the procedure combined with its minimization of scarring, trauma, and operating room and recovery time. The procedures are performed with the use of long slender tools, inserted into the body through small incisions in the skin and underlying membranes. Small camera lenses are inserted through other, nearby, incisions to provide visual access to the site of the operation. Because only small incisions are made, trauma to the patient is reduced when compared to conventional, open surgery. This reduction in trauma subsequently leads to reduced recovery time, allowing the patient to return to normal activity much sooner. Due to the increase in popularity of these procedures, a large number of physicians require training. Currently, training is done in one of three ways: on a plastic model, either with or without fluid; on a cadaver; or, on a patient. A virtual reality training simulator could be more realistic than the first two methods, while maintaining a higher level of patient safety than the last method mentioned.

Through conversations with surgeons and use of the current state of the art in haptic devices, it was clear that for this application, point forces would not be sufficient. During arthroscopic procedures, the shaft of the tool that the surgeon is holding passes through a portal into the patients knee, thereby limiting the motion of the device. Additionally, while an experienced surgeon might not feel any large moments on the tool during surgery, a new surgical resident will require a learning period to adjust to the constraints of the surgical setup. During this period, the resident will be more likely to unintentionally hit structures with the shaft of the tool he is holding, generating moments when measured about the tip of the tool. There are three main contributors to moments acting on the tool: the fibrous membrane that the tool shaft passes through and levers against; inadvertent contact between the shaft of the tool and structures inside the knee; and, when exploring the back compartment of the knee, pressure from the collateral ligaments.

Because these moments are very important when learning these procedures, a device that can display moments is required. Instead of designing and building a completely new device, an addition to the Phantom haptic interface was deemed most tenable, in terms of both cost and performance. A completely new device would take much longer to design and build, and given the constraints of the task domain, breaking the problem down into two parts provided simplicity: one part, the Phantom, generated the majority of the force to display to the user; the second part, the new device, generated a planar force at a point along the shaft of the tool, thereby generating a moment measured about the tip of the tool. The 2 DOF device is a planar device with a 4 DOF gimbal attached at the distal end. The gimbal allows free motion of the tool shaft around all rotational axes and along the axis of rotation of the shaft. It constrains the shaft of the tool to pass through a point on a plane. An analogy would be to view the world as a hollow cube, with the shaft of the tool constrained to pass through a point in the center of one side of the box. The tip of the tool is connected to a Phantom to measure position and apply point forces. The 2DOF device is then placed on the side of the box, and the shaft of the tool passes through the gimbal. Motion of the 2DOF device will apply moments to the shaft of the tool that will be felt by the user. In this manner, two force vectors acting on the shaft of the tool at distinct points, a force and moment are generated.

II. DEVICE DESCRIPTION

The 5 DOF consists of a 2 DOF planar device and a 3 DOF device, the Phantom. The shaft of the tool handle connected to the Phantom passes through the 4 DOF gimbal of the planar device. In this manner, the planar device can only apply forces in the plane to the shaft of the tool. When this planar force is combined with the general point force applied to the tip of the tool handle by the Phantom, a force and moment are generated.

The 2 DOF planar device is a classic five bar mechanism. The two inner links are the same length, as are the two outer links, although the inner link lengths and the outer link lengths are different. This symmetry provides for a more well conditioned and symmetric workspace. Link lengths were generated using data from [1], to provide a workspace of sufficient size based on design criteria described in the next section. Hard stops are provided to limit the inner links motion, and to allow for accurate zeroing of the motors at a known angle. A stop is also built into the outer links to keep the device from going through its singularity, when the angle between the outer links is 180 degrees.

The 4 DOF gimbal attached to the distal end of one of the outer links is designed to allow free motion of all uncontrolled degrees of freedom of the device, i.e. all motion out of the plane of the device. In that manner, the gimbal allows free rotation about all axes and translation along the tool's long axis. Two of the rotational degrees of freedom utilize simple rotational bearings, while the third rotational degree and the translation degree of freedom are enabled by a plane linear bearing, which allows both free translation and rotation.

The inner links are driven by Maxon servo motors through a tensioned cable drive. Direct drive motors were investigated, due to increases in performance through decreased static friction and inertia, but sufficient position resolution was not found to be possible. Motor choice was based on similarity to the Phantom motors, so that standard Sensable Technologies, Inc. amplifiers could be used.

III. General Design Criteria

Video tape of arthroscopic knee surgery was acquired to help determine workspace requirements. The video was analyzed to find out how much motion of the tool portal occurs during typical procedures. Angular excursions of the probe were also ascertained. The motion of the portal roughly describes a circular disk with a diameter of approximately 1", dependant on the patient. The angular excursion of the tool, with respect to the normal direction at the portal location, describes a cone with a 120 degree included angle, again, dependant on the patient.

Gear ratio is determined by the desired nominal position resolution, given 500 count encoders that are standard on Maxon motors. Nominal position has both inner links at 45 degrees from horizontal.

Interference between the device and the user's hand is also an issue. The motors of the device protrude in the direction normal to the motion of the device. With the motors pointing into the workspace, interference with the Phantom is possible. Preferable to this is to have the motors sticking out of the workspace, with possible interference with the user's hand. To minimize interference, the motors were spread as far apart as possible, to allow more clearance through the center of the device. Direct drive motors would have caused the most interference in this case, since their location can not be modified. The motors were also moved back from the plane created by the proximal ends of the inner links, again to minimize interference.

IV. Mathematics of Planar Device

The planar device is a closed chain device without simple symmetry, unlike the Phantom. Therefore, the forward kinematics and Jacobian calculations are more difficult and computationally expensive. Position of the endpoint based on motor angles is calculated through the determination of the interior angles of the device.

Referring to Figure 1, b is the horizontal distance between the proximal end of each of the two inner links and the origin of the workspace, O. l_i is the length of the ith link. θ_i is the angle of the ith link. θ_{d3} and θ_{d4} are two of the interior angles of the triangle formed by the two outer links and the line joining the distal ends of the inner links. a is the vertical distance and d is the horizontal distance between the distal ends of the inner links, while c is the shortest distance between them and θ_a is the angle between c and the horizontal, and has a negative value in Figure 1.

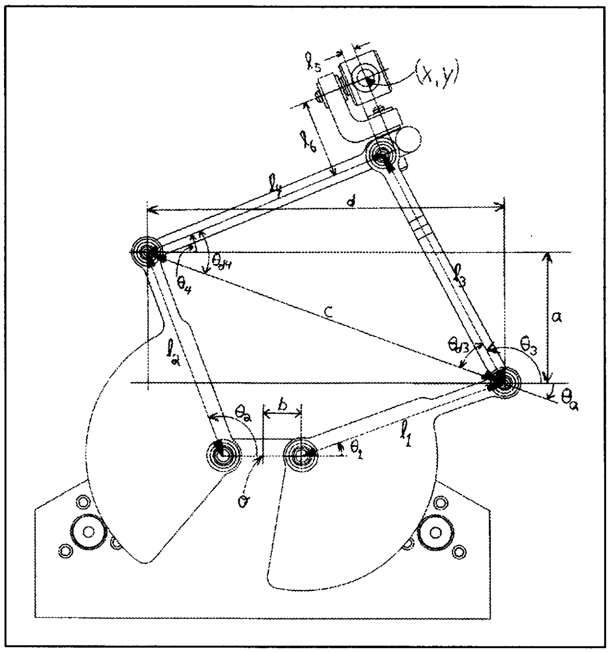

Figure 1 Schematic of planar device

Then d, a, and c are determined through simple geometry, and θ_a is the inverse tangent of a over c. θ_{d3} and θ_{d4} are calculated using the law of cosines, and then θ_3 and θ_4 are once again determined through simple geometry. The position of the endpoint of the five bar mechanism, (x, y), is then determined through geometry, where l_5 is the distance between the distal end of the outer links and the center of the gimbal along the axis of link 4. l_6 is the distance between the distal end of the outer links and the center of the gimbal normal to the axis of link 4. The Jacobian J is calculated in the usual manner to facilitate the determination of the motor toques, τ, to apply to the actuators to achieve the desired force $\vec{F_d}$. The equations described above are as follows:

$$d = 2b + l_1\cos\theta_1 - l_2\cos\theta_2 \quad [1]$$

$$a = l_1\sin\theta_1 - l_2\sin\theta_2 \quad [2]$$

$$c = \sqrt{a^2 + d^2} \quad [3]$$

$$\theta_a = \operatorname{atan}\frac{a}{d} \quad [4]$$

$$\theta_{d3} = \operatorname{acos}\frac{l_3^2 + c^2 - l_4^2}{2l_3c} \quad [5]$$

$$\theta_{d4} = \operatorname{acos}\frac{l_4^2 + c^2 - l_3^2}{2l_4c} \quad [6]$$

$$\theta_3 = \pi - \theta_{d3} + \theta_a \quad [7]$$

$$\theta_4 = \theta_{d4} + \theta_a \quad [8]$$

$$x = b + l_1\cos\theta_1 + l_3\cos\theta_3 + l_5\cos\theta_4 + l_6\cos\left(\theta_4 + \frac{\pi}{2}\right) \quad [9]$$

$$y = l_1\sin\theta_1 + l_3\sin\theta_3 + l_5\sin\theta_4 + l_6\sin\left(\theta_4 + \frac{\pi}{2}\right) \quad [10]$$

$$J = \begin{bmatrix} \frac{\partial x}{\partial\theta_1} & \frac{\partial x}{\partial\theta_2} \\ \frac{\partial y}{\partial\theta_1} & \frac{\partial y}{\partial\theta_2} \end{bmatrix} \quad [11]$$

$$\tau = J^T\vec{F_d} \quad [12]$$

Referring to Figure 2, the way in which the forces at the tip and at the point where the shaft passes through the gimbal of the planar device are generated by the following relations. $\vec{F_T}$ is the total force to be felt by the user, and $\vec{M}$ is the moment to be felt by the user.

Given the values of $\vec{M}$ and $\vec{F_T}$, and the vector $\vec{S}$ between the tip position of the tool and the linear bearing of the five bar mechanism, the forces to generate at the tip and through the collar can be determined. Let w represent the world coordinate frame where all positions and forces are measured and d be the coordinate frame of the five bar mechanism where $\hat{Z}_d$ is normal to the plane that the device moves in. Then, ${}^{w}\vec{P_p}$ is the position of the tip of the tool and ${}^{w}\vec{P_d}$ is the position of the five bar mechanism. $\vec{S}$ is the vector from the five bar mechanism position to the position of the tip of the tool, while $\hat{S}$ is the normalized direction of $\vec{S}$. Similarly, $\hat{M}$ is the normalized direction of $\vec{M}$.

First, the minimum force vector which would generate the moment $\vec{M}$, $\vec{F_d}'$, is calculated at the five bar mechanism position:

$$\vec{F_d}' = (\hat{M} \times \hat{S})\frac{|\vec{M}|}{|\vec{S}|} \quad [13]$$

$\vec{F_d}'$ will normally not lie in the plane defined by the five bar mechanism, but will always satisfy the moment equation, $\vec{M} = \vec{S} \times \vec{F_d}'$. It is also always perpendicular to the vector $\vec{S}$.

Next, the force $\vec{F_d}'$ is projected onto the plane of the five bar mechanism, so that the force applied by the device, $\vec{F_d}$, will also satisfy the equation $\vec{M} = \vec{S} \times \vec{F_d}$. This projection force, which is perpendicular to the force, $\vec{F_d}'$, is generated by:

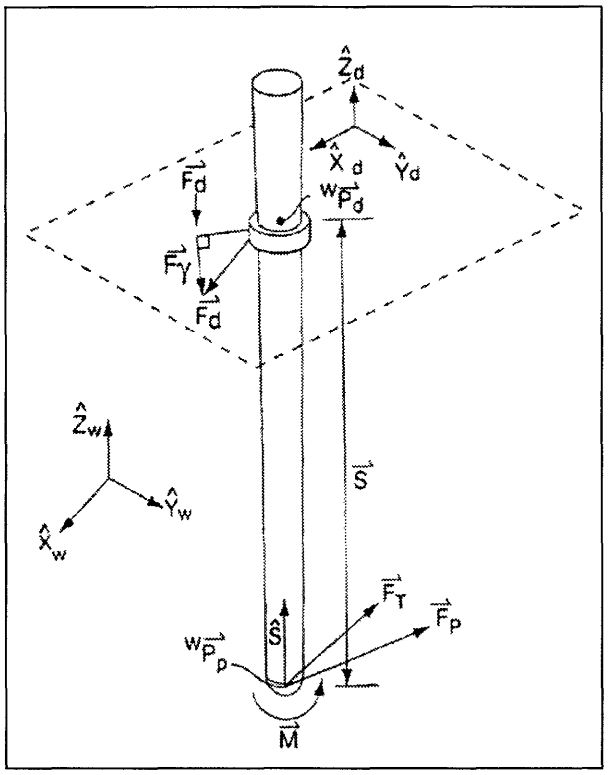

Figure 2 Device force determination

$$\vec{F}_\gamma = \left(-\frac{\hat{Z}_d \cdot \hat{F}_d'}{\hat{Z}_d \cdot \hat{S}}\left|\vec{F}_d'\right|\right)\hat{S} \qquad [14]$$

The force that will be generated by the five bar mechanism is the vector sum of $\vec{F}_d'$ and $\vec{F}_\gamma$:

$$\vec{F}_d = \vec{F}_d' + \vec{F}_\gamma \qquad [15]$$

The force applied to the tip of the tool is $\vec{F}_p = \vec{F}_T - \vec{F}_d$, to maintain the total force displayed to the user.

V. Results

Given the workspace requirements outlined above, and charts from [1], links lengths for the inner links, outer links, and spacing between the inner links were generated. The distance between the proximal ends of the inner links is 0.875", the inner link length is 2.375", and the outer link length is 2.813". There is also an offset along the outer link to where the gimbal is attached, and that length is 0.150", while the perpendicular distance from the outer link to the center of the gimbal is 0.854". The diameter of the drum of the inner links is 1.500" and the diameter of the cable capstan is 0.360", providing a gear ratio of 8.333. Given the above gear ratio and link lengths, the nominal position resolution is 0.0007", or 1450 dpi. These link lengths generate a workspace with a diameter of 1.875", which allows the planar device to be placed away from the surface of the simulated skin, allowing a phantom skin model to be physically placed within the working area of the devices to add to the realism for the user. The skin model also allows users to visually position themselves and the tool within the simulated world.

Two example applications have been implemented. The first is a simple simulation of simple geometric objects, in which the user can lever the tool between multiple objects, thereby generating large moments on the tool shaft. The other simulation is of the tip of a surgical probe interacting with a volumetric description of a knee, while the planar device servos on a point. This simulation doesn't explicitly generate and display torques, but in the same manner as above, the two distinct forces do generate a force and moment. The planar device servoing on a point could also be viewed as similar to the force generated by the fibrous membrane surrounding the knee. Qualitative results from the second application were mixed. These mixed impressions are believed to be caused in part by most user's unfamiliarity with the physical setup of arthroscopic surgery, where the tool passes through a portal. Results from the first demonstration application were very positive, showing the power of displaying more than a point force when interacting with complex environments.

VI. Acknowledgments

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Tactile Max: A Haptic Interface for 3D Studio Max

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Introduction

The creation of realistic haptic objects and environments for use with simulation and procedural training has, in the past been relagated to tedious OpenGL programming techniques. This required programming in c++ with the GHOST SDK and/or OPEN GL. What was needed in our opinion was a more rapid way to create a touchable virtual environment. Research indicated that a PC/NT based full featured animation program like 3D Studio Max would be ideal for the development of a plug-in that would allow the PHANToM to interact with objects created or imported into the animation software. By using Max as the platform for development we can take advantage of all of the modeling and animation tools as well as 3D models that already exist. This allows extensive, complex data sets to be made haptic very rapidly.

3D Studio Max SDK

The 3D Studio MAX SDK provides a comprehensive set of classes that developers can use to create plug-ins. The Tactile Max is a modifier-type plug-in and from user's point of view it is simply a button added to the Modify command panel for the 3D Studio MAX user interface. Because MAX plug-ins are modeless, Tactile Max comes in and out of focus, as the system requires processing on its part. The classes created by the plug-in provide procedures to be called when needed.

The modifier plug-in type was chosen in particular because it allows modification of objects in the 3D Studio MAX scene dynamically in any of the MAX viewports. This functionality is necessary to make a mesh object haptic because the GHOST Polymesh class requires that the topology of a mesh object consist of all triangles. So the object itself must be modified. Another reason the modifier plug-in type was chosen is that it is a part of the Geometry Pipeline System.

The GHOST SDK

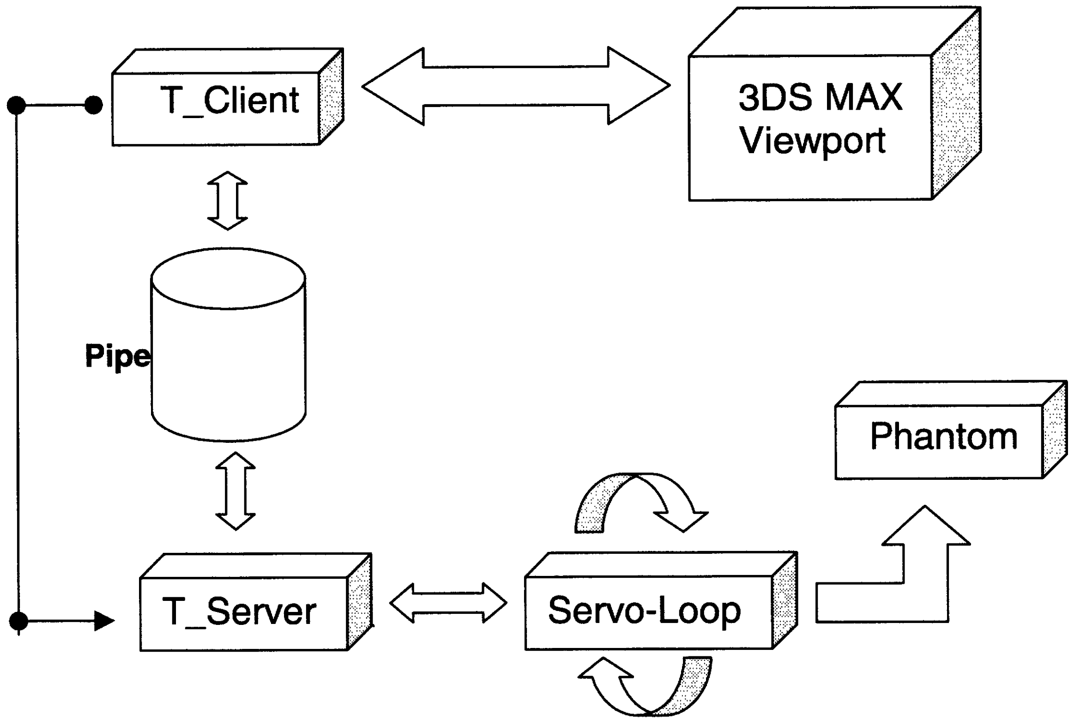
The GHOST SDK was used in the development of Tactile Max. GHOST stands for General Haptics Open Software Toolkit. The GHOST API (application programming interface) enables application developers to interact with PHANToM haptic device and create haptic environments at the virtual object level. The GHOST SDK does not generate visual representations of objects within the haptic scene graph, [1]. It does however provide graphic callback mechanisms to facilitate integration between haptics and graphics domains. These mechanisms were used to interface the PHANToM with 3D Studio Max.

Application Design

The application is composed of two primary processes. A client process (running inside 3D Studio MAX) and a Server process, running separately controlling the PHANToM haptic device. This setup is desirable because it allows decoupling of the low-level force servo loop from the high-level control. This is important since the haptic servo loop must run at a very high rate, typically greater than 1000Hz, to achieve a high fidelity force display, [2]. Another reason for this setup is that the GHOST SDK and the MAX SDK use conflicting naming conventions for their data types. By separating the two processes and using a pipe in memory for inter-application communication the problem is solved. Having the two processes separated means that the application can run across a network on two different computers. The haptic server receives high level commands from the client, tracks the position of the haptic device, updates the position of the proxy, and sends control commands to the haptic device.

The client side of the application is the Tactile Max modifier that is placed on a 3D Studio Max object. The client queries objects and converts objects (composed entirely of polygons) into tri-objects. This is done to get the mesh in the right format for the GHOST SDK class gstPolyMesh that is used to create the haptic representation of the object. GstPolyMesh is a class that describes the haptic object as a set of triangles. After queries about the object's topology the client side of the application returns information on the number of vertices, the number of faces (polygons), the XYZ position's of the vertices, and an index of point adjacency for each face. The server uses this information to instantiate a GHOST gstPolyMesh object.

At this point the server sends messages confirming the creation of an object and it is added to the scene graph. XYZ coordinates are then passed and the client side of the software in Max tracks the Phantom's stylus tip. The following figure represents the software architecture of the plug-in.



Comments and Conclusions

The haptic interface will be useful for many types of applications that can be built on this framework. These applications will have the ability to interact with the objects in more than one way. For example in a hypothetical medical simulation a layer of skin could be removed to see an underlying bone by clicking the stylus button and holding shift. The ability to dynamically change the object and see it updated in a Max viewport will be useful in the event that this software is extended to support the simulation of soft-bodied objects.

A 3D painting program could be created that would allow artists to interact with their media palpably using the friction capabilities of the PHANToM. Modern 3d Painting programs do not incorporate any direct feedback from the object being painted to the user. They allow you to paint on an object in 3D but do not allow you to feel the object being painted. Adding a haptic interface to the paradigm would extend the current technology. Being able to feel the object that you are painting and simulate brushes and pencils would be an advantage to any 3D artist involved in the creation of realistic 3D objects, creatures, and humans.

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Implementation Issues in Adding Force Feedback to the X Desktop

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ABSTRACT

This paper describes implementation issues encountered in a project to add force feedback to the X Window System desktop in an attempt to add true "feel" to the window system's "look and feel". Haptic additions to the interface include adding ridges around icons and menu items to aid interaction, alignment guides for moving windows, and a number of other enhancements to window manipulation. The issues discussed here include the precise descriptions of the forces computed, as well as lower-level issues such as how to achieve those forces with GHOST.

INTRODUCTION

Graphical user interfaces (GUIs) have long involved haptics in what amounts to an accidental manner: the feel of mouse buttons being pressed, the feel of keys on the keyboard, and the friction and proprioception involved in moving the mouse all give feedback that comes entirely from the basic physical properties of the input devices and does not change with the state of the human-computer interaction. Although these forms of accidental haptic feedback often correlate with the user's input and prove useful during interaction, in the context of the virtual environment that GUIs seek to provide they are still impoverished compared with the rich feedback of real-world interactions. Adding explicit program control of haptic feedback can radically change an interface, adding true "feel" to its "look and feel" and potentially leveraging additional real-world skillsets.

This paper focuses on the implementation issues encountered in the initial stages of a project to add haptics to standard GUI elements of the X Window System [Scheifler–92], using a 1.0-workspace PHANToM [Massie–96] with encoder gimbal.

PREVIOUS WORK

Rosenberg and Brave [Rosenberg–96a, Rosenberg–96b, Rosenberg–97] have worked on enhancing 2D GUIs with 2-DOF input/2-DOF output devices, while Münch and Stangenberg [Münch–96] enhanced a 2D GUI somewhat differently, using a modified mouse with vibrotactile and braking feedback to add predictive target acquisition aids. Our system provides different DOFs and manipulation affordances from the devices used in these approaches, thus leading to different interface choices.

Many of the demos that come with the PHANToM and GHOST have 2D arrays of haptic buttons and sliders arranged on a plane as part of their interface, as does the FLIGHT system [Anderson–97]; each of these may be regarded as effectively a 3D haptification of a very simple 2D user interface, albeit with 3D-looking visual feedback. Adding haptics to the existing X desktop is further constrained by dealing with existing applications and existing 2D visual feedback, leading to different interface choices; in addition, different interface elements were haptified in this project, involving different haptic techniques.

X DESKTOP TECHNIQUES

We added force feedback to icons, windows, and menus by adding dimples, ridges, negative viscosity, pressure sensitivity, and buttonlike clicks; see [Miller–98] for further details about how these techniques were used. The basic workspace for the haptification was a shallow box $50\ \mathrm{mm} \times 40\ \mathrm{mm} \times 2\ \mathrm{mm}$ whose longer two dimensions corresponded to the 1280×1024 screen and were horizontal; the tip of the stylus was constrained to remain inside the box. Nearly all the forces in the implemented techniques occur through interaction with the surfaces of the box, possibly with slight changes in their geometry (ridges added along windows, for instance). The bottom is the primary interaction surface; the sides merely prevent the stylus from getting out of range; and the upper surface has a mirror image of all the interaction features of the lower surface and in addition one special interaction for raising windows.

IMPLEMENTATION

Architecture and X Interface

The system was implemented on an SGI R10000 O2 using SensAble Technologies' GHOST toolkit. The X pointer was controlled through the fairly standard XInput extension; an SGI addition allows new input devices to be made available through that extension simply by writing a loadable kernel STREAMS module rather than having to recompile the X server. Communication from the clients to the haptics server was done by setting X properties on the client windows.

Because the PHANToM has only one button but typical X interaction requires three buttons, the haptics server uses the XInput extension to open the mouse device and forward its middle and right button states as though they were the PHANToM's. Since many styli made for use with tablets come with multiple buttons, it is to be hoped that future PHANToMs will remedy this deficiency by adding more buttons. The user's interactions while pushing down to slide windows and pulling up to raise them were communicated by pretending that the PHANToM XInput device had two extra buttons, whose events were then intercepted by the window manager.

Forwarding the normal mouse's button states requires the haptics server to get data back from the X server. However, X allows a client to grab the server, halting all transations with all other clients. Because certain interface techniques wait for a button release before releasing the grab, but the button waited for may be one of the forwarded ones, the haptics process uses the XTEST extension to make itself immune to X server grabs and thus prevent deadlock.

The Generic Window Manager, gwm (available by anonymous ftp from `ftp.x.org` in `contrib/window_managers/gwm`), was haptified first because it is programmable in a form of Lisp, thus not requiring recompiling to make interface changes. As a result, its C-code modifications were only slight, primarily to allow setting of X properties on the window manager's windows rather than just client windows.

The haptics server implements its own message queue for input received from X, via the main loop, to the haptics thread. Since it seems better the haptics thread miss a (relatively infrequent) update from X and thus reflect incorrect state for one millisecond than to subject the user to unexpected jerking or even have the program exit because the haptics thread was waiting for the main loop, a design goal for the synchronization of this queue was that the haptics thread should never block. Instead, if the queue lock is unavailable, the haptics thread simply continues simulation with possibly old data. However, once the haptics thread has registered an interest in the lock, the main thread is prevented from reacquiring it until the haptics thread has gotten its chance, thus avoiding starvation. Since another project used a version of this locking strategy on NT, code exists to implement it on NT as well as Irix. On Irix it can be implemented directly using the Irix polled semaphore facility, but on NT the implementation is more complicated, involving both a Mutex and an Event and relying on poorly documented behavior of the Event object.

Haptic Details

General Issues Trying to use the stylus as a pen with the PHANToM in its standard orientation (rotated $90°$ clockwise from Figure 1) makes the armature interfere with the stylus and user's hand, often resulting in unintentional button clicks. To address this, the makeshift mounting shown in Figure 1 was used. Unfortunately, the stylus encoders are not counterbalanced in this position, giving rise to a force attempting to twist the stylus out of the user's hand. Makeshift counterbalances were attempted, but the most promising approach seems to be to use the new desktop PHANToM, which lacks the ungainly stylus encoders. The bottom of the haptic workspace was moved as close as possible to the physical desktop to encourage a stylus grip approximating that of a normal pen, and a handrest made of four stacked mousepads was used to lift the user's hand to about the level of the virtual desktop. That virtual desktop is currently horizontal, although some tilt towards the user might well be better.

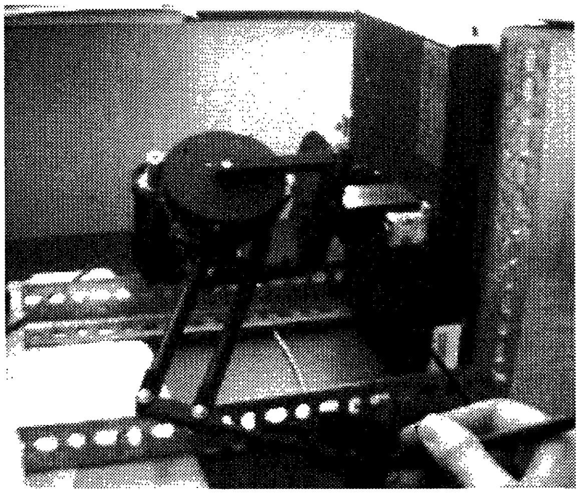
Figure 1: The 1.0-workspace PHANToM in its tilted home.

Many of the force parameters in the implementation were simply guessed at and not adjusted, because the initial guess worked out well. For a few, however, a little closer attention has been paid: friction is set to approximate that between pencil and paper while maximizing pointer movement controllability, with resulting static and dynamic friction coefficients of 0.15. The basic surface spring constant was set to $0.8\,\mathrm{N/mm}$, and the user must exert at least 3.2 N downward to slide windows; this is a compromise between larger values, which produce discomfort and intermittent loss of the window, and smaller values, which produce accidental window movement.

GHOST's implementation of friction appears to prevent the reported SCP position from moving all the way to an inner corner of an object. Apparently, the tangential force in GHOST is computed by comparing the stiction point with the SCP reported by the object, rather than the user's position. (The algorithm used to implement friction in GHOST is presumed to be similar to that in [Salisbury–95] because their behaviors match and because at least two of the authors are involved with SensAble.) This means that when the user comes to a concave-outward corner that "traps" the SCP, the stiction point remains some distance away from the corner,

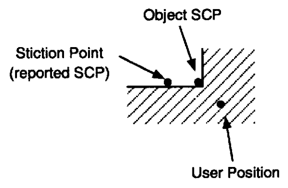

Figure 2: GHOST's implementation of friction can prevent the SCP from moving all the way to the edge of an object.

no matter how hard the user pushes (see Figure 2). Since the stiction point appears to be what GHOST reports as the SCP value to the user interface, the cursor cannot be moved all the way to the edge of the screen in the presence of friction. The difference is small in physical terms, but very noticable on screen with the large magnification from the haptic workspace to the application screen size. It also gets worse as the user grows more frustrated and thus presses the stylus down harder, increasing the force of static friction.

To work around this problem, GHOST's friction constants are set to zero, and the object's SCP computation routine implements friction itself. The object maintains its own stiction point, which is simply what it last reported as an SCP (it can't just use what GHOST reports as the previous SCP because that value may be different if other objects are interacting with the SCP). The SCP computation routine computes a "frictionless SCP", which would have been the reported SCP in the absence of friction, and a "pseudo-SCP", which is the projection of the user's current position onto the line between the frictionless SCP and the stiction point. If the stiction SCP and frictionless SCP do not share any face of the object in common, the stiction point is simply set to the frictionless SCP. Otherwise, it is moved towards the frictionless SCP following the algorithm of [Salisbury–95], using the pseudo-SCP for the user's position. The computed stiction point is then reported as the SCP for the object.

Low-friction surfaces in GHOST feel as though they have more friction than they should; this is apparently because GHOST's implementation of surface contact damping damps velocity in all directions whenever the stylus is in contact with a surface. This program works around this problem by implementing its own damping with a gstEffect that damps only the velocity component normal to the surface.

Technique Implementation Part of the haptification of menu items, icons, and windows was done by dimpling them into the lower surface of the workspace, as shown in Figure 3. The sides were always at a 45° slope and one pixel wide for all elements except drag-and-drop targets, which had 12.5-pixel-wide sides. The dimples were thought of as volumes subtracted from the workspace bottom; intersection testing was done by finding the first intersection with a surface (of a dimple or the workspace) not inside the region cut away by another dimple; this simplified calculations for intersecting dimples and in particular obviated the need to explicitly compute polygonal CSGs. Making the dimples just abruptly disappear, for instance when a menu is removed, would put the PHANToM suddenly underneath the surface and thus displaying no forces; instead, the system offsets the workspace by the depth of the dimple and gradually restores it to its original position at a rate of $1\,\mathrm{mm/s}$. The program causes GHOST to maintain most of the SCP positions properly by using a gstDynamic subclass to do the offset restoration, but needs to explicitly modify the stiction point recorded to implement friction to keep it maintained properly as well.

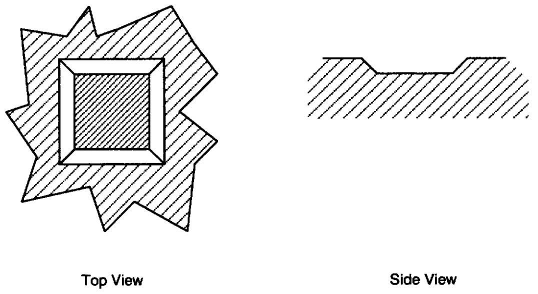

Figure 3: Geometry of the haptic dimple used in menu items, icons, and windows.

Another common haptification technique involved using *infinitesimal ridges*, places where the reported SCP is constrained not to move outside of some area. This constraint feels to the user as though there is a little ridge on the surface that disappears as soon as the stylus is lifted off. In some cases the user can "pop through" the ridge; this was implemented by temporarily suspending the constraint on the SCP if the user exerted more than $2\,\mathrm{N}$ sideways against the ridge.

An earlier, very preliminary pilot project explored using negative viscosity in the direction of potential targets for drag-and-drop operations. The original implementation used $0.002\,\mathrm{N\,s/mm}$ in the direction towards the target and positive viscosity of the same absolute value in the direction perpendicular to the direction to the target. From our preliminary observations this negative viscosity has little significant effect, and few people notice—presumably because the implementation is so gentle that it merely offsets viscosity naturally present in the device itself, the user's hand, etc. Higher levels of around $0.004\,\mathrm{N\,s/mm}$ are noticeable, but feel disruptive and destabilizing.

The user was allowed to raise windows by pulling up against the top of the workspace over the window; the sensation was like pulling up on an inverted physical button. Pulling up where there is no window that can be raised simply feels like a normal hard surface, so that the haptic feedback matches the possibility of performing the operation. The program implements the buttonlike "click" by computing its own normal force in a gstEffect subclass that works in conjunction with the desktop object. Another implementation possibility would have been to use a gstDynamic subclass to move the whole workspace; the approach used here was chosen instead because code already existed from another project that couldn't use the gstDynamic approach. A standard button model was simulated with an initial springy area and hard stop having the same spring constants as the rest of the ceiling, while the dead band had a restoring force of $0.5\,\mathrm{N}$. The pointer is considered to be over a window that can be raised when it is contained in any mapped, non-override-redirect top-level window but not contained in any mapped, override-redirect top-level window.

CONCLUSIONS

Adding force feedback to 2D GUIs seems to be a promising area to explore, and the GHOST environment seems to be flexible enough to handle that exploration without too much implementation difficulty. Although the PHANToM 1.0 has problematic ergonomics for this application, the new desktop model appears to be a significant improvement.

From our preliminary observations [Miller–98], some of the techniques implemented, such as using dimples in drag-and-drop operations, seem to make a noticeable improvement in interaction speed, while one, adding the dimples used here to menu items, has a noticable negative effect. Further research is clearly needed to investigate what techniques work under what conditions. (Since another paper [Rosenberg–96b] reports increased performance with a different haptification of menu items, presumably the problem with the dimples lies in the technique and not in the general idea of haptifying menu items.)

Debugging the details of some of the more complicated haptic behavior of this system has been laborious, apparently largely because the haptics update rate is so fast and force feedback itself essentially involves the physical world to such an extent that most debugging techniques entailing stepping through the code or stopping the program to examine its state become useless. In addition, the simulation is computationally demanding enough that even running a debugger on the program at all can significantly change its behavior or cause it not to work. Currently, the program has been instrumented to record various hoped-to-be-pertinent values that are then dumped on receiving a trigger and plowed through by hand to find the problem. In the future, however, it would be much nicer to have an organized facility to record this data and then display the results graphically, with the ability to use a debugger in conjunction with a playback mechanism.

ACKNOWLEDGMENTS

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ASSEMBLY SIMULATION THROUGH HAPTIC VIRTUAL PROTOTYPES

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*Abstract : this paper describes a haptic CAD environment that has been developed by means of the link between a haptic device (**PHANToM**, Personal Haptic iNTerface Mechanism, SensAble Technologies Inc USA) and a CAD system developed by LABEIN (**DATum**, an object oriented non-manifold variational geometric modeller). The integration of both systems allows the user to interact with the 3D designs in a new and more realistic way than the traditional systems: now the user can not only view the objects designed in the CAD environment, but also touch, grasp and move them by the virtual space detecting the possible collisions with other objects. This may have multiple applications, but this work is focused in the simulation of assembly and maintenance operations of mechanical components.*

1. INTRODUCTION

The Virtual Reality is a powerful technology that can help and solve some of the limitations of the traditional simulation systems. Most of the current virtual reality tools are focused in the visualisation and navigation providing the user with the feeling that he is inside of a real environment. However, the impossibility of touching objects or detecting collisions among them makes more difficult a complete user-environment integration.

On the other hand, a 3D CAD design of a mechanical assembly provides information about its size and components, but this information is insufficient to deduce the assembly or disassembly sequence. It is at this point where the Virtual Reality can have an important role, allowing the user to get into a "virtual world" by means of special tools (glasses, helmets, etc., ...) and simulate different assembly and maintenance operations of mechanical components. This would be a great aid for the designers and maintenance personnel.

This paper describes a haptic CAD environment that has been developed by the integration of a geometric modeller and a haptic device that allows the user to interact with the objects designed in the CAD system, in a more realistic way than the traditional systems. The geometric modeller that has been integrated with PHANToM and the haptic CAD environment that has been developed are described in the following sections.

2. *DAT*um

DATum is an object oriented variational non-manifold geometric modeller developed by LABEIN, with a STEP translator compliant with ISO 10303-AP203 (International Standard for the representation and the exchange of product data between different CAD systems) and a VRML translator.

DATum uses a hybrid representation scheme between the two most common representations within the field of the Geometric Modelling: the Constructive Solid Geometry (CSG, see [5]) and the Boundary Representation (B_rep, see [4]), exploiting the advantages of each one of these representations. In this way, any model has associated a boundary representation and can be defined by a tree data structure whose nodes are the Boolean operations (union, intersection and difference) and whose leaves are: primitive models (blocks, cylinders,...), general B_rep models or others CSG trees.

DATum is a non-manifold modeller [6]. This capability allows to represent solid, surface and wireframe models in an unified and simultaneous way and to deal with the "region" concept. In this way, a model can be composed by several regions associated, for example, to different materials.

DATum is also a variational modeller. The variational geometry is based on the definition and modification of geometric models through a set of functional restrictions, instead of the classical parameters. In this way, the model can include the design intent.

3. THE HAPTIC CAD APPLICATION

The haptic CAD environment that has been developed allows the user to interact with any object designed within ***DATum***, or translated from another CAD system through STEP files or translated from VRML files, making use of different utilities: touch, move, detect collisions and simulate assembly and maintenance operations. All the objects that are being manipulated with PHANToM are visualised on the screen, being possible the use of stenographic glasses to get a more realistic perception.

The objects that can be manipulated with the new application can be solid or surface models and be defined by conics (lines, circles and ellipses), quadrics (planes, cylinders, cones, spheres, torus) or geometry more complex like b_splines curves and surfaces.

The work flow of the integration between ***DATum*** and PHANToM is the following:

1. The user creates the 3D model/s with ***DATum*** graphical interface and/or imports the geometry from another CAD system through the STEP interface or from a VRML file.
2. The device PHANToM is activated.
3. ***DATum*** gets the position of PHANToM (corresponding to the position of the user's finger), analyses it according to the utility that is being used and calculates the force that is necessary to send PHANToM.
4. The force is sent PHANToM.
5. Goto step 3.

As has been mentioned above, four main capabilities have been implemented: touch, move, detect collisions and simulate assemblies.

3.1 Touch

The user can touch any 3D object and move himself along its external surface, detecting edges and corners. In addition to the 3D object a point that indicates the position of the user's finger (the position of PHANToM) is visualised on the screen.

The algorithm to touch objects is based on the analysis of the position of PHANToM with respect to the object. If the object is a solid model that generates a closed volume, it will be necessary to check if the point is inside or outside of the volume. If the object corresponds to a surface model it will be necessary to check if some of its faces is being gone through. In order to reach the constant frequency required by PHANToM (1000 Hz) it has been necessary to define some special strategies depending on the type of the model and its geometry.

Primitives
In the case of primitive models, such as blocks, spheres, cylinders and cones, some simplifications can be made according to the specific geometric features of each one of them.

General Models
In the case of a general model the implemented strategy is based on local checking, i.e. the analysis of a point is based on the position of the last studied point with respect to the model. There are three possibilities:

1. The previous point was out of the model. In this case to check if the new point is inside or outside of the model, it will be necessary to intersect the line that joins both points (the last and the new one) with all the faces of the model. This is the most global checking.
2. The previous point was inside of a face of the model but not on its boundary (i.e. it was not on an edge of the face). In this case, the minimum distance point to the face is calculated to compare the movement direction with the normal vector to the face on the minimum distance point.
3. The previous point was a vertex or was on an edge of the model. In this case, it is necessary to check if the movement direction is inside of the model and get the minimum distance points to the adjacent faces to the corresponding vertex/edge.

If the model is a surface model an additional checking has to be done to take into account the side of the face where the user's finger point is located.

In order to implement this strategy it has been necessary to optimise and adapt some algorithms already implemented in ***DAT**um* to increase their efficiency. Some of these algorithms are:

- Algorithms to check if a point is inside of a volume or a face
- Algorithms to calculate the intersection between curve-curve and curve-surface
- Algorithms to get the minimum distance points between point - curve, point - surface and point - face

3.2 Grasp and Move

Any object that can be touched can also be grasped and moved by the user. There are two types of movements: simple translations, when only one PHANToM is used, or general transformations including rotations, when two PHANToMs are used.

The user can move his finger along the virtual workspace until touching an object (with one PHANToM) or grasping it (with two PHANToMs), from then on the object is moved together with the user's finger. The movement described by PHANToM (by the user's finger) is applied to the object in order to transform its position.

In this case, the force sent PHANToM corresponds to the friction force (if only one PHANToM is used), or to the object weight (if two PHANToMs are used). This has required the implementation of some algorithms to calculate the volume and the area of any 3D object.

3.3 Collision detection

This utility detects any collision between an object that is being moved with PHANToM and any other object of the working space. In this way the object can not penetrate into another and only real feasible movements are allowed. The implemented algorithm deals with one moving object and any number of static objects. It can be divided in three phases, see [1], [2] and [3]:

1. Analyse the collisions among the boxes containing the 3D objects in order to detect the possible collisions in a fast way.
2. Analyse the collisions among the faceted models of the objects whose boxes were intersecting. In this algorithm, a boxes hierarchy containing the model is created in order to facilitate the detection of the parts of the models (if any) that can be colliding.
3. Analyse the collisions with the exact geometry of the models, if a more precise collision detection is required. This phase is undertaken after the first two ones have been done and only with the parts of the models that have been detected during the above phase.

When a collision is detected the user is not allowed to move in the collision direction, but he can change the movement direction in order to avoid the collision. Sound aids have been implemented to warn the user when a collision is produced.

3.4 Assembly

This capability is used to simulate the assembly/disassembly process of a mechanical component. All the other capabilities, Touch, Move and Collision detection, are enclosed here. The two specific assembly methods that have been developed are described below.

Assembly two objects with three pairs of coincident surfaces
This method is used to simulate the assembly of two objects with three pairs of coincident surfaces (see the middle drawing of the figure 1). Each pair of surfaces is assembled consecutively. This algorithm consists of four phases:

1. The user moves himself by the working space until touching one of the objects.
2. This object is moved together with the user's finger until finding the first pair of coincident surfaces.
3. The object is slid (through sliding forces) along the coincident surface until finding the second pair of coincident surfaces.
4. The object is slid (through sliding forces) along the intersection line between the surfaces of the two pairs of coincident surfaces until finding the third pair of coincident surfaces

Insert a pin in a hole
This method is used to simulate the insertion of an object "pin" in a hole, checking if the object "pin" collides with other objects of the working space along its movement (see the last drawing of the figure 1). The hole can have any shape (circular, quadrangular, etc.,...) and can be a through all hole or not. The algorithm consists of three phases:

1. The user moves himself by the working space until touching the "pin" object.
2. The "pin" object is moved together with the user's finger until finding a common assembly axis with the hole.
3. The "pin" object is slid (through sliding forces) along the assembly axis until the two objects are assembled.

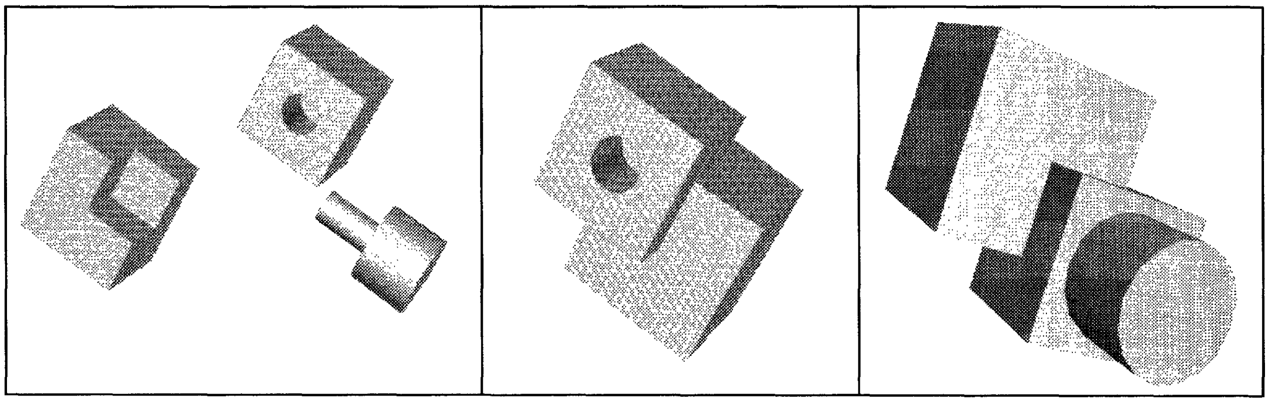

Fig. 1. Different Assembly Methods

4. CONCLUSIONS

In recent years the Physical Mock-Ups are being replaced by Virtual Prototypes. In this way, computer data models are being used as the core part of the design process where the users can work on the same model and perform several analyses to validate the model. This allows reduced costs, lead time and better competition.

Nowadays, the Virtual Prototypes have a broad range of utilities, but do not cover all the utilities provided by the physical models. One of these topics is the interface between the user and the model. The sense of touch is one of the most important human tools to perceive and analyse an object and it is something missing in the Virtual Prototypes. Haptic interfaces can add this missing piece and make more realistic the interaction between the user and the virtual world.

The work presented in this paper tries to fill this gap integrating a haptic device and a general CAD tool. The user can touch, grasp and move 3D CAD models feeling like interacting with real parts. The main focus is the simulation of assembly and maintenance operations of mechanical components. Although many other applications may be also addressed.

5. ACKNOWLEDGMENTS

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Springs and Constraints for 3D Drawing

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ABSTRACT

In this paper we present examples of haptic sculpting mediated by a physical model or constraint. Most current work in haptic drawing and sculpting focuses on interacting with a static model and properly simulating contact forces. Our work proposes dynamic models for the creative process. These are based on physical models, but present physically impossible scenarios which allow new forms of expression. By focusing on models not realizable in the real world we show an expansion of the creative process through haptic feedback.

As example applications we present two prototypes. *Dynasculpt* allows 3D sculpting by attaching a sprung virtual mass to the Phantom position and creating a ribbon or tube along the path taken by the mass through space. *Griddraw* is used for constrained 3D drawing – a uniform 3D grid of detents is haptically superimposed over 3D space, allowing the easy production of straight lines and right angles. Both focus on dynamics as intrinsic to the creative process.

Our initial reflections and observations indicate that this paradigm is a fruitful one for haptically enhanced creation of static models. The standard problem of users comparing their experience to the superior real-world experience is circumvented in this work by presenting novel experiences impossible to feel or construct in the physical world. By presenting ourselves and naïve users with simple target tasks, we have informally analyzed the controllability of each tool. Our two prototypes seem to lie on extremes in a continuum of expressivity/controllability – Dynasculpt can become difficult to control – often at the edge of chaos, while Griddraw can be overly constraining. Active force feedback in both cases can serve to stabilize unstable or chaotic models.

INTRODUCTION

A natural and immediately apparent use for haptic feedback is in the area of three-dimensional modeling. Architecture, industrial design, and sculpting all benefit from natural haptic feedback. Real-world haptic feedback is present in scale models of works-in-progress: architectural models, sculptural maquettes and full-scale industrial prototypes. Haptic feedback is also present in tactile building materials such as clay, foam, wood, metal and plastic. Most current work in the haptic enhancement of sculpting, drawing and architectural design focuses on the first problem – haptic rendering of a rigid, usually static model via simulation of contact forces [1].

The majority of the work in haptic modeling has focused on the simulation of real-world materials – particularly hard geometric objects. This approach suffers from two problems based on comparison with the real world phenomena. First, only single-point contact forces are possible using the Phantom and users may find this manipulation weak in comparison to the full tactile/kinesthetic feedback provided by real materials. Second, the low refresh rate and smaller forces of the Phantom suffer in comparison to the real-world phenomena.

At Interval, we are exploring non-physically based dynamic models for haptic sculpting, sketching and drawing. We believe that providing experiences based in dynamic systems, but not directly reflecting real-world phenomena is a fruitful approach to creative expression with haptic devices. By using a model not based in reality, we provide the users with an experience otherwise impossible to achieve – giving them new creative potential. At the same time, the tools discourage comparison with the real world because the models are not based on real phenomena. Our initial experiments in this realm are described in this paper. A deeper exploration of this space and further applications will appear in a future publication.

PRIOR WORK

In the graphics community there are a number of examples of interactive sketching without haptic feedback, notably the 3D geometric sketching work done at Brown University [2], Paul Haeberli's image-based impressionistic painting algorithms [3] and the 2D non-photorealistic sketching at the University of Washington [4]. Passive haptic feedback in a sculpting application was attempted in the Sculpt application [5].

A strong inspiration for us is an application called *Dynadraw* by Paul Haeberli [6]. Dynadraw is a drawing program that connects a virtual mass to the cursor position via a damped spring. As the user draws, the path that the mass follows is stroked, instead of the mouse position. This creates smooth, calligraphic strokes (Figure 1). This application is the first example we know of which mediates

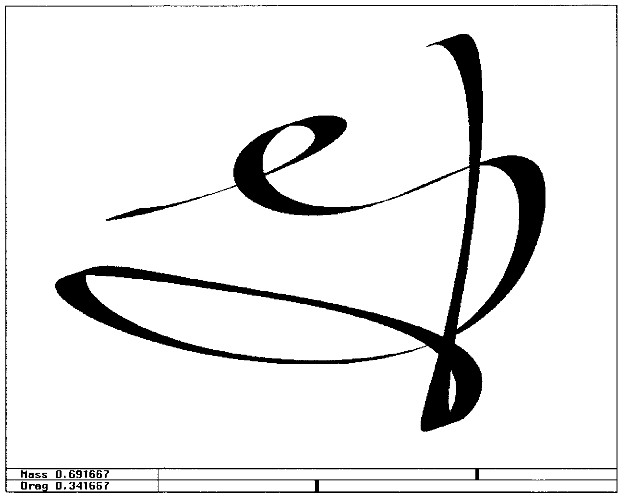

Figure 1. Paul Haeberli's Dynadraw.

a creative experience (drawing) through a physical model. Dynadraw involves no haptic feedback. Our first explorations in haptically mediated sculpting involve adding haptic feedback to a similar application.

APPLICATIONS FOR DYNAMIC SCULPTING

DYNASCULPT

Dynasculpt allows sculpting by attaching a virtual mass to the 3D Phantom position and constructing a ribbon or tube along the path taken by the mass through space. A linear, damped spring is used to attach the mass to the finger position (Figure 2). The spring force between the mass and finger is calculated using Hooke's law with a damping term:

$$\mathbf{f} = -k(\mathbf{x}_m - \mathbf{x}_f) - b\dot{\mathbf{x}}_m$$

where k is the spring constant, b is the damping constant, $\mathbf{x}_m$ is the virtual position of the mass and $\mathbf{x}_f$ is the real-world finger position as measured by the Phantom. The position of the mass can be expressed as a Newtonian system:

$$m\ddot{\mathbf{x}}_m = -k(\mathbf{x}_m - \mathbf{x}_f) - b\dot{\mathbf{x}}_m$$

where m indicates the mass. We solve this second order differential equation using Euler's method. Continuous haptic feedback is provided to the user by applying the equal and opposite force -**f** to the user via the Phantom. The user is also provided with two "clutches". The first controls whether the pen leaves a stroke through space – controlled via the Phantom stylus button. The second is a spring-loaded force enable on the keyboard. Users can modify the mass, spring constant and damping via sliders.

Drawing is significantly altered by haptic feedback (**Error! Reference source not found.**). In purely physical terms, the user's hand is pulled towards the mass point. If only a modest force is applied, the Phantom cursor is drawn along behind the virtual mass and both soon come to a rest. Without haptic feedback, the dynamics are those of a fixed point attached to a moving mass - in the original Dynadraw and in Dynasculpt without haptic feedback, the finger position is in effect nailed rigidly to the virtual mass with no intervening dynamics. The simulation consists of, in the case of Dynasculpt, movements which are opposite but balanced; whereas with Dynadraw it reflects the movement of the mass alone. Dynasculpt demonstrates the distinction between real and virtual objects in a haptically enhanced environment. The position of the virtual mass is updated via discrete steps in a simulation, while the position of the real mass must be updated through a human user's reaction to real forces. By understanding implication of this difference, we can start to find the applications where haptic feedback presents valuable and novel experiences.

Via informal evaluation of our colleagues and our own experiences going back several years, we have observed other ways in which haptic feedback alters the sculpting experience. As users interact with the system, they can often build up quite a strong rotational inertia in the virtual mass. The kinesthetic feedback provided by the Phantom helps them to fine-tune their speed and inertia to create a desired periodic behavior. We find that removing the force feedback results in less controllability in these cases. When the damping constant is reduced in the original Dynadraw or in Dynasculpt, small changes tend to continually add energy into the system, resulting in wildly oscillating and sometimes exploding dynamics. As soon as haptic feedback is introduced into these under-damped systems the human operator's muscles and reflexes serve to naturally damp the system. This is one of our more important (if obvious) observations, that a human operator can serve to dampen chaotic or overly energetic systems. Thus, the dynamic system can operate closer to the limits of the system without becoming unstable.

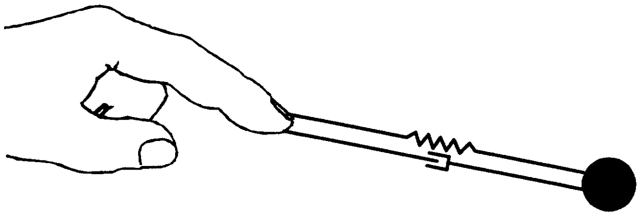

Figure 2. Dynamic model for Dynasculpt.

GRIDDRAW

A typical problem encountered in 3D sculpting applications is effectively navigating the 3D space [5]. Using 2D screens is an obvious cause of this problem, but even in experiments with stereo or immersive displays, users' movements tend to be uncoordinated and unsteady. These sculptors have trouble both maintaining and guiding their absolute position through space [7].

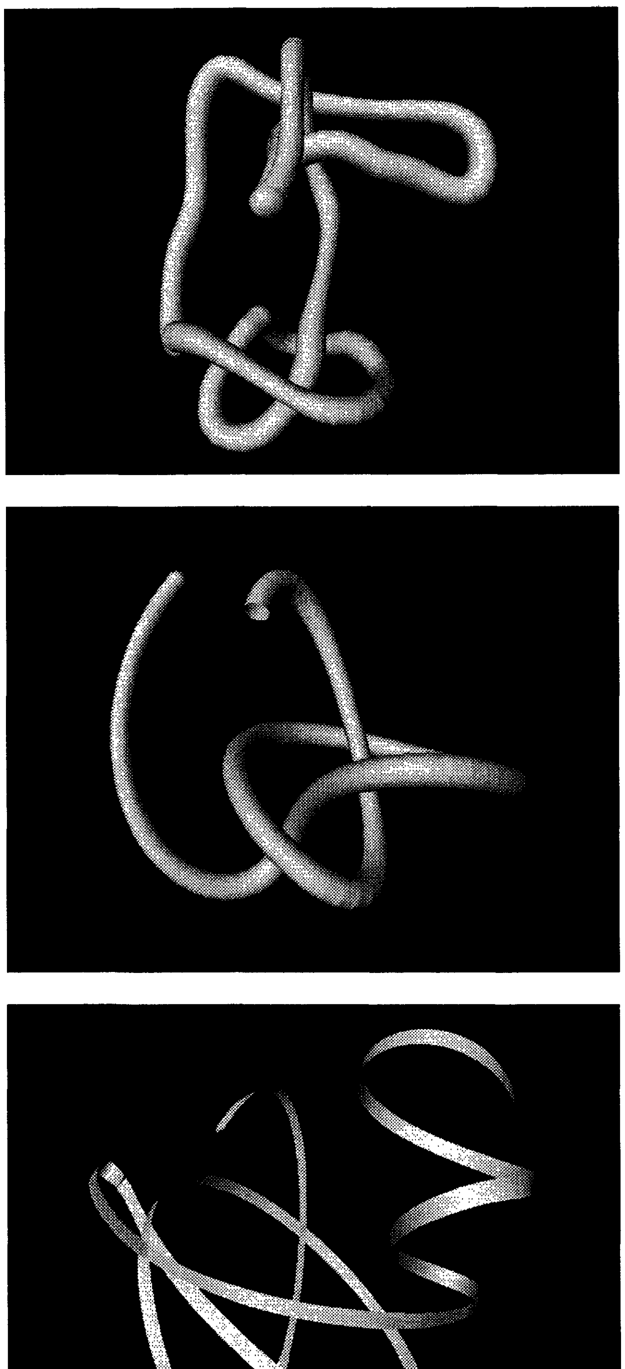

Figure 3. Dynasculpt. Different sculptural qualities can be achieved by varying the dynamic parameters. All three drawings used the same spring constant. With low damping and small mass, rapid oscillations induce wiggles in the shape (top). High damping and large mass result is smooth, slowly varying shapes (middle). High mass and moderate damping result in relatively quick variation while still smoothing the path (bottom).

Figure 4. Griddraw force vectors (2D slice).

Griddraw is an experiment in constrained sculpting. We chose the simplest possible constraint we could think of – a 3D grid. This grid is created by haptically overlaying a sinusoidal force grid on top of the 3D Phantom workspace:

$$\mathbf{f} = k_s \sin(k_g \mathbf{x}_f)$$

where k_s is the strength of the grid force and k_g is the density of the grid spacing (Figure 4). This results in two qualitatively different constraints. First, motion is naturally constrained along the orthogonal X, Y, and Z-axes, easily enabling straight lines to be drawn (Figure 5). Second, the Phantom maintains its position when a user lets go of the stylus. Thus, work is more naturally picked up and put down, without the clumsy fumbling to locate a particular position in three-space.

We certainly found that our users could draw straight lines quite easily. Further, users were able to more easily complete drawing tasks, such as drawing a cube. Finally, users were more likely to move along the Z-axis, moving into the space of the screen. We experimented with two drawing methodologies. The first methodology actually constrained the on-screen sculpture to the grid-lines. Our second algorithm exactly stroked the path followed by the stylus, even when straining against the constraint, and we find the latter method more interesting. With normal constrained drawing in a non-haptic application using a mouse and a graphic display, the former method is the only one available – the on-screen object's movement or structure is modified by the constraint. With haptic feedback, the user has the choice to follow or diverge from the constraint. A continuum of behavior is possible without switching modes. Thus force feedback allows a constraint to be followed in degrees, rather than the binary constrained/unconstrained choice.

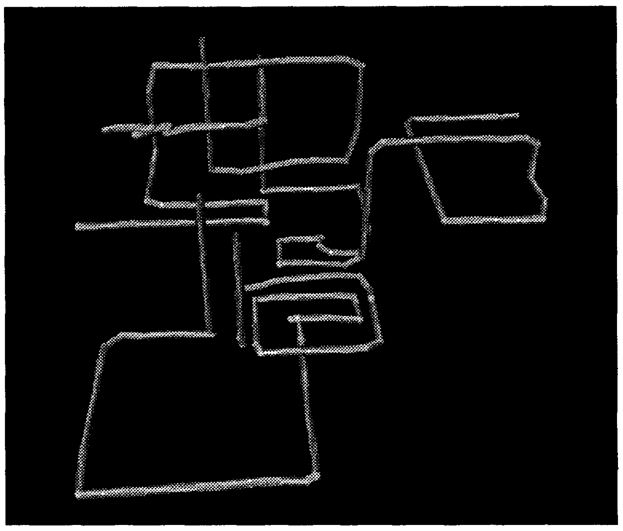

Figure 5. Griddraw. Lines do not travel along precisely straight lines, since the grid constraint is imposed haptically rather than graphically.

IMPLEMENTATION DETAILS

Both Dynasculpt and Griddraw are implemented on an SGI Indigo^2 R10K. We run in two separate processes which communicate through shared memory. The graphics process is implemented using Inventor and is refreshed at a constant rate of 30Hz (subject to degradation due to graphics performance). Our custom software updates the haptic process at a constant 2.5Khz using the real-time scheduling provided by the IRIX 6.5 OS and communicating directly with a Phantom SW Desktop model. Since our model is a simple one, we can update the mass/spring/damper system at the haptic refresh rate. The graphics process looks at the computed values for mass and finger position whenever a new frame is drawn. We have found real-time scheduling to be a reliable method for obtaining guaranteed haptic refresh rates using a single processor SGI machine. However, one must take care to insure that computation doesn't exceed the allocated time-slice. Models that have no constant or upper bound on time complexity are unsuited to this solution.

OBSERVATIONS AND REFLECTIONS

We believe our two applications lie near the extremes of a large space of dynamic sculpting applications. Dynadraw presents a near-chaotic model in which the system is fun to play with, but most users find it difficult to achieve any drawing goals. A seemingly simple task of drawing a knot was only successfully achieved by only a small percentage of our users. In contrast, Griddraw presents an over-constrained system – it is easy to achieve certain drawing goals, but the tool only allows a limited range of expression. Both applications are similar in that their dynamic models enforce a strong style on the works created.

We found that despite using a 3D input device, many users worked only in the plane parallel to the computer screen while sculpting. We are not certain if this is due to prior experience – being accustomed to mice, tablets and other 2D devices – or if this is a natural expression of human creativity. Do we tend to think and create in planes? Does our body geometry encourage movement in planes? Or is it the experience of seeing a 2D display that dominates the experience?

FUTURE WORK

As we further explore this space we would like to find applications in the middle ground between Dynadraw and Griddraw. More controllability is essential to a tool for real-world tasks. More sophisticated constraints might influence the users' style to a much lesser degree – for example constraints sensitive to specific orientations, speeds or positions.

We would like to administer more formal testing of our applications with a set of drawing tasks. We also would like to experiment with stereoscopic displays as a more natural 3D display. We also think that a comparison between stereoscopic and monoscopic displays will help us to understand the tendency to draw in planes.

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Network Access to a PHANToM Through VRPN

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Abstract

At UNC-CH, we have several graphics engines, several force-feedback devices and several applications that make use of each. Each application uses the force device, graphics engine and location most favorable to it. This requires flexibility in providing access to devices, and has for several years pushed us to provide switched video capabilities for our graphics engines and network connections for our force devices.

Recently, we have built our network access on top of the GHOST toolkit to access the PHANToM force-feedback devices in our laboratories. This access is through our Virtual-Reality Peripheral Network (VRPN) library. This library allows an application to treat a PHANToM like the other tracker and button input devices in our laboratory while also allowing it to provide force output.

We present the VRPN/GHOST interface and some applications that have used it fruitfully.

Introduction

It has been known for some time that it is proper to uncouple the low-level haptic rendering of simple representations of objects from the high-level simulation of complicated objects. (Adachi, Kumano et al. 1995) The GHOST toolkit separates haptic update from both graphics and simulation using a separate haptic rendering thread that communicates with the main application through shared memory. This is a very effective solution for single-machine applications. Other toolkits provide a network link between the application process and the haptic display process, using either TCP/IP or a mix of TCP/IP and UDP/IP for updates. (Mark, Randolph et al. 1996; Ruspini, Kolarov et al. 1997) This approach allows the use of multiple computers within a single application (one computer more suited for graphics and one more suited for haptics). It also introduces network latency and possible loss into the system.

Our environment is one of several different display stations, each of which has its own particular tracking technology (optical/mechanical, magnetic, custom optical). (Arthur, Preston et al. 1998; Grant, Helser et al. 1998; Welch and Bishop 1998) The displays are driven from a number of graphics computers, with analog video switched between them. Applications use whichever station suits them best, often moving from one station to another. This requires hooking each graphics engine up to each tracker at various times. To enable this, we have developed a set of servers that sit on the network, each one running the tracker and button input devices at a particular location. We have developed a library to enable applications to talk work in the same manner no matter which physical device they are connected to. This library is called the Virtual Reality Peripheral Network (VRPN). (Taylor II 1998)

VRPN

The Virtual-Reality Peripheral Network (VRPN) is a set of classes within a library and a set of servers that are designed to implement a network-transparent interface between application programs and the set of physical devices used in a virtual-reality (VR) system. The idea is to have a PC or other host at each VR station that controls the peripherals (tracker, button device, sound, etc). VRPN provides a connection between an application and all of its devices using the appropriate class of service for each type of device sharing this link. The application remains unaware of the network topology.

VRPN also provides an abstraction layer that makes all devices of the same base class look the same; for example, all tracking devices look like they are of the type vrpn_Tracker. This merely means that all trackers produce the same types of reports. At the same time, it is possible for an application that requires access to specialized features of a certain tracking device (for example, telling a certain type of tracker how often to generate reports), to derive a class that communicates with this type of tracker. If this specialized class were used with a tracker that did not understand how to set its update rate, that tracker would ignore the specialized commands.

The VRPN client (application-side) library has been tested on SGI/Irix, PC/Win32, HP700/Hpux and PC/Linux. The server-side library compiles under SGI/Irix, PC/Win32 (not yet for serial-port devices) and PC/Linux. VRPN is in the public domain; information about downloading the system can be found at http://www.cs.unc.edu/Research/nano/manual/vrpn.

Connection

The heart of the VRPN library is the vrpn_Connection class. This class dispatches messages locally and across network connections, delivering the messages using callback handlers. Application code does not normally deal directly with the vrpn_Connection class, but rather accesses it through one or more device classes. It is the device-specific class which deals most intimately with the vrpn_Connection class. Thus, only those writing device classes need to thoroughly understand how this class works.

All messages in VRPN have a time, a sender and a type associated with them. The time is defined by the sender, and usually corresponds to the time at which the action generating the message occurred (local clock time). For example, the vrpn_Button class reports the time that a button was pressed or released. Clock synchronization is performed between the client and server when a connection is established so that all time values reported to a particular machine are relative to its local clock.

Application code deals with various objects layered on top of the vrpn_Connection class. Each type of object (tracker, button, force device, etc) implements both a client-side type which the application uses and a server-side type specific to each particular device.

Trackers

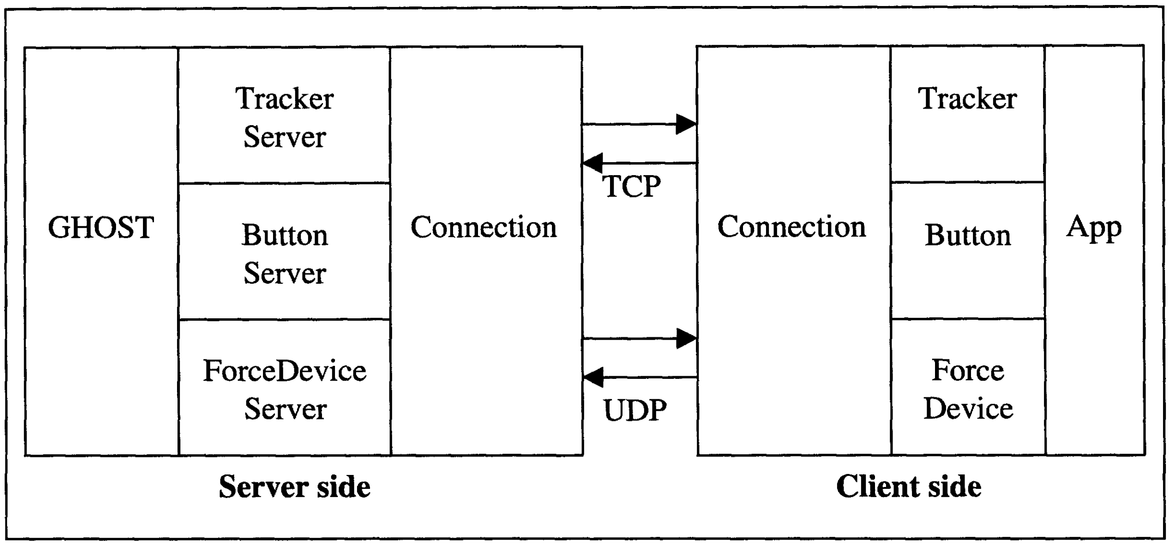
Vrpn_Tracker objects report their position and perhaps velocity and acceleration. Some trackers allow the application to specify the rate of reporting; others ignore this request. Orientation is specified as unit quaternions. (Shoemake 1985) Trackers with multiple sensors send a report for each. Tracker commands (such as requests to send at a certain rate or requests for parameters) are sent over the network reliably, as are their results. Tracker reports are sent unreliably, since it is better to wait for a new report than to spend time re-sending an old one that has been lost.

Buttons

Vrpn_Button objects report press and release events, and the time at which the event occurred. They can be set to toggle or momentary under application. All button messages are sent over the network reliably.

Force Devices

Whereas tracker and button devices are primarily for input, the vrpn_ForceDevice is used for output. The application sends local surface representations to the device, which it presents haptically to the user. These representations can be meshes (which are mapped to the GHOST mesh primitive) or local plane approximations (which are implemented using the GHOST callback feature). Controllable surface parameters include the stiffness and friction. For the visualization of multiple data sets, were are also adding the capability to provide textures and vibrations to simulated surfaces.



PHANToM Over VRPN

When an application opens a force device, such as the PHANToM, it also wants access to the position reports from the device and also any buttons that are on the device. The application gets access to these by opening the device with the same name as a vrpn_Tracker_Remote, a vrpn_Button_Remote, and a vrpn_ForceDevice_Remote. VRPN takes care of mapping all of these devices to use the same connection to communicate over, and the application treats the three separate functions of the device independently. Since devices ignore unrecognized messages, it is possible for applications that use force feedback to connect to a normal tracker for testing of the input function and only to a force device when needed. It is also possible for applications that do not require force feedback to use the PHANToM as a tracker and button device, ignoring its force capabilities.

Applications

VRPN was originally designed for use by generic virtual-reality applications. The particular application that required use of the PHANToM was the nanoManipulator. (Finch, Chi et al. 1995) This application uses a single plane to approximate a surface being scanned by a probe microscope; the plane is updated as new data arrives from the microscope tip.

There is also a group at Wright Patterson Air Force Base that is implementing a version of the Docker program (see (Ouh-young 1990)) using a PHANToM. They are working with NCSA on the development of new force-display algorithms for this extremely difficult simulation. They are developing a new force model that presents not a surface but a force field.

We are also using this system as a base for the investigation of alternate collision-detection algorithms. (Gregory, Lin et al. 1998) This work uses meshes as the local representation of remote geometry. Simpler early work by Adam Seeger implemented a Venus fly-trap model that would close and trap the user if they were not quick enough after tripping the trap.

Conclusions and Comments

Good things: VRPN provides normalization of devices while still allowing specialization. It runs either locally or across the network. It is extensible, in that either new devices or new classes of devices can be created within its framework. This makes it easy to use a PHANToM within a multi-device environment, allowing access to it from any computer on the network. VRPN is in the public domain. You can have the source code.

Bad things: VRPN does not present the GHOST interface to the application. This means that existing PHANToM applications cannot use it directly without change. It would be possible to write a GHOST-like layer on top of the VRPN client library that would allow applications to link with it rather than GHOST, but that is not the direction we are headed so it won't be done by us. VRPN is not supported as a product.

If you are using or planning to use PHANToMs in a heterogeneous or networked environment, we would like to work with you to extend VRPN for your situation. We can be reached at vrpn@cs.unc.edu.

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Acoustic Cues for Haptic Rendering Systems

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Abstract

The addition of sound to haptic application can greatly increase the level of immersion and sense of presence experienced when interacting with a virtual environment. In this talk we will present some preliminary work to incorporate acoustic cues into a constraint based haptic rendering system. The objective of this work is not to create physically realistic sounds, which depend heavily on the structure and composition of an object, but rather to allow a developer to artistically place sounds on an object to give an impression of the object's makeup. In addition, because of the high computational costs associated with both haptic and graphic rendering, a primary goal has been to introduce these acoustic cues with minimal impact on the overall performance of the system. To achieve this requirement a number of compromises were made to permit the bulk of the sound processing to be performed by the dedicated sound synthesis hardware, found in most computers.

1 Introduction

Sound generation has always had an important role in the creation of immersive multi-media applications. In haptic systems, sound cues can be used to identify properties of an object that may be difficult to discern solely from visual or tactile clues. The identification of an object's composition, be it wood or metal, can normally be done with just a few taps on the object. Sound cues can also increase the sense of solidity perceived by a user while interacting with an object. This sensation can be utilized to reduce the mechanical stiffness and actuator effort requirements of a haptic device or increase the apparent stiffness that can be displayed. Lastly sound cues are very useful in aiding on-lookers in understanding the nature of the haptic interaction, which can at times be baffling when only the visual cues are available to them.

It is extremely difficult to classify the wide range of sounds found in nature or used in computer applications. In our work we focused on a few types of sounds that are of particular interest for haptic interaction. These are sounds caused by impacting or striking an object (impact sounds). Sounds created while sliding in continuous contact with a surface (contact sounds); and lastly sounds generated by dynamically interacting with an object, such as slamming a door, or turning a squeaky wheel (event sounds). In this brief paper, we will only discuss sounds created by impact. Our work on contact sounds, and event sounds is left to a future paper.

2 MIDI/Wave-Table Synthesis

To limit the impact of sound generation on the computational requirements of the haptic rendering system it is desirable to make as much use as possible out of the existing capabilities of sound synthesis hardware. In our implementation, the capabilities of the MIDI/Wave-Table Synthesis found in many of the most popular sound cards was utilized. While the full capabilities of the MIDI specification are impossible to describe in the limited space available, in looking at the sounds caused by impact only a few attributes are of importance. MIDI allows sampled sounds to be stored on the memory of the sound-card. For impact sounds the sample are organized in a manner very similar to how percussion sounds are stored in more typical MIDI applications. A collection of samples is stored in a sound font which can be loaded prior to starting the haptic display. To start a sound requires just sending a short command to the sound card and demands very little CPU overhead. The sound will continue until either the sound has completed or it is stopped by application. Only a limited number of sounds can be playing at one time. For example in our current system, using an AWE64 SoundBlaster only 32 "voices" can be active at one time. This necessitates prioritizing the sounds that are to be played as will be seen in section 3. Lastly the sound can be modified by changing its volume, left/right pan, reverb or pitch. These capabilities are be used to help spatially distribute the sounds in the workspace.

3 Sampling and Playing Sounds

In our approach, the impact, contact and event sounds are all sampled separately from real objects using commercially available software. For each sample a envelope is constructed which roughly defines the amplitude of the sample at a given time. Because almost all impact sounds can be described as having a strong initial attack phase and a subsequent exponential decay, an envelope described by the function $f(t) = Me^{-dt}$ is used, see figure 1. Where M is the initial magnitude and d is the decay parameter selected on the basis of values in the sample. In addition the total duration and dominant frequency are stored to describe the high level characteristics of the sample.

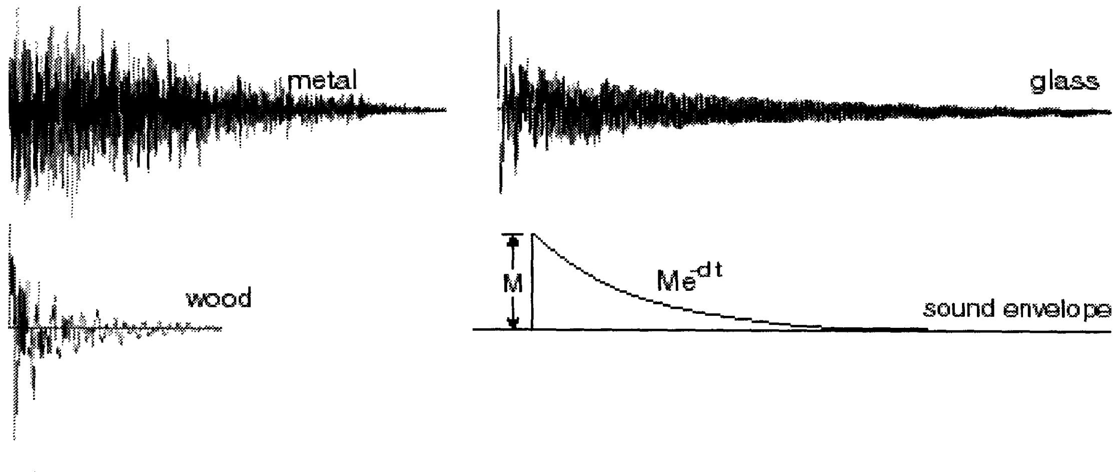

Figure 1. Different materials exhibit different waveforms when struck (metal, glass, wood). A simple decaying exponential envelope can be defined to described to generalize the magnitude of a given sound after a given time

Because of the limited number of voices available and the large number of sounds that may be requested, not all sounds can be played to their completion. When a new sound is issued a list of active voices is checked to see if a free sound channel is available. Given the small number of active voices this check can be performed very rapidly. If no slot is available the sound with the smallest magnitude, based on its envelope, is stopped and the new sound started. If the new sound has a magnitude less then all currently active tones then the note is discarded. Because MIDI can only play one sequence of a given note, if an existing note is reissued then the new magnitude is compared with the old to determine if it will replace the previous note. Typically for a given surface a number of notes are assigned and cycled through sequentially to reduce the chance that a given sound will be cut off prematurely. The rapid decay and short duration of most impact sounds prevents most sounds from being cut off before they become inaudible.

4 Implementing Impact Sounds

In constraint-based haptic rendering systems a representative object is used to represent the position of the user's finger or hand in the virtual world. In our current system "HL" [2] this object, called a proxy, is modeled as a massless sphere which one can imagine to be attached to the end of the user's finger by a stiff spring. Because of the massless nature of the proxy its velocity is not well defined. A low pass exponential filter is used to approximate the velocity of the proxy at a given time.

$$v_p^+ \doteq \frac{u(x_p^+ - x^- p)}{\Delta t} + (1-u)v_p^-$$

where $0 \leq u \leq 1$ is an exponential parameter which is determined empirically, x_p^+ and x_p^- is the position of the proxy at the beginning and end of the cycle respectively, v_p^+ and v_p^- are the old and new estimates of the velocity and Δt is the total cycle time of the update loop.

When a contact with an object in the environment occurs an instantaneous change in the velocity of the proxy occurs.

$$\Delta v = \hat{n}^T(v_o - v_p^-),$$

where $\hat{n}$ is the unit vector normal to the surface, and v_o is the velocity of the object. When $\Delta v < 0$ the proxy and object are separating and no collision occurs. A sound proportional to Δv is created for the given surface material to model the impact with the surface. The velocity of the proxy is subsequently updated so that another impact is not created on the subsequent passes through the low pass filter velocity estimator.

$$v_p^+ = v_p^- - \hat{n}\Delta v.$$

Numerical issues, and details in the implementation of the proxy update loop can and often do create multiple subsequent impact events. These impacts being of very small magnitude are often pruned by the scheduler described in Section 3.

5 Sound Textures

As described above the impact sounds for a particular material are issued whenever an impact is detected on a surface. These sounds tend to be repetitive since the same sound is played on each impact with the surface. These sounds also do not convey any information about the internal structure of the object since the same sound is generated at any point on the surface. In order to allow more compelling environments to be created a sound texture can be applied allow different sounds to be applied at different positions along the surface. An example of such a sound texture is shown in figure 2. The texture is an artistic interpretation of the sounds created when a door is struck at different locations and is not intended to be physically correct. The texture roughly represents the stiffness of the object at a given position.

To create the sound samples, for the example in Figure 2, the original door sound is passed through a progressive set of low-pass filters to filter out the high frequency components. The resulting samples have progressively a more hollow/lower tone. When mapped on the surface the resulting object has a more solid realistic sound signature. The surface material can be easily changed when the characteristics of the door change, as illustrated in 2. If the textural value at the point of impact lies between the values for two sound samples, two options are possible. One option is to select at random one of the two neighboring samples with a probability based on the how close the textural value is to the value of each sample. Another option is to issue both sounds simultaneously with the volume of each based on the distance to the given textural value.

Additional texture channels can be used to change other characteristics of the surface such as the constant of proportionality between the velocity of the impact and the volume of the sound or the amount of reverb applied to the sound. In our future work we hope to allow multiple sound layers to be applied to a surface to allow even more compelling and realistic sounds to be created.

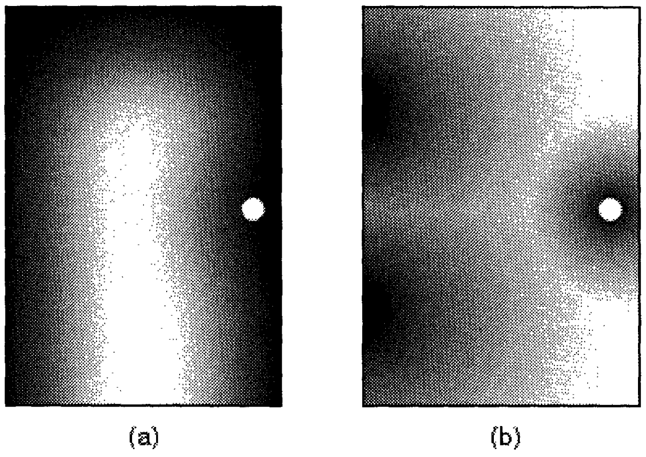

Figure 2. Sound textures are used to paint sounds, such as those corresponding to the stiffness of the material, on the surface of an object. Sound textures can be changed instantly to reflect different states of the system, such as the door being closed(a) or open(b).

6 Conclusion and Future Work

The techniques we have described coupled with contact and event sounds help in creating a compelling multi-sensory experience. A great deal of work, however, remains to be done to allow sounds to be more easily incorporated into haptic applications. The creation of the sound fonts is still a very slow and manual process. We are looking at several ways of automating the sampling process. One possibility is to use a small manipulator, such as the Phantom, to hit or slide along an object to create sound images automatically. Another direction of future research is to use multiple textures to store different vibration modes as described in [1] and play multiple samples (generated either artificially or filtered from sampled sounds) to play a resultant composite sound based on the excitation of the vibration modes of the object.

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SCIRun Haptic Display for Scientific Visualization

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Introduction

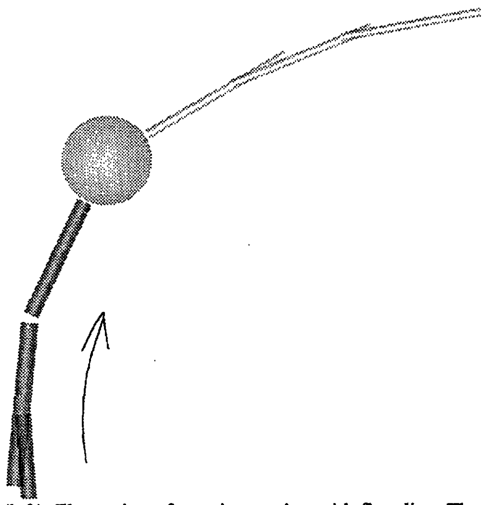
The overall goal of this research is to enhance scientific visualization by the use of haptic feedback. We have chosen to approach this goal by incorporating a haptic interface into an existing full-featured scientific visualization tool.

People who use scientific visualizations are generally trying to analyze or solve a scientific problem. The visualizations are usually animations or interactive graphics that scientists create for themselves. The visualizations are intermediate representations intended to represent the problem or its solution graphically (1, 2). Ideally these visualizations are accurate, information-rich, interactive, and illustrative of key features of the phenomenon or data set. They should make the problem (or its solution) easier to understand. Toward this goal we augmented existing graphical visualizations with force feedback (3), as well as true 3-D interaction, in ways that highlight key features such as flow lines. The haptic interface we have developed allows the user to form a high-level view of his data more quickly and accurately.

Scientific visualization research has been underway at the University of Utah for much of this decade (4). One outcome of that research is a problem-solving environment for scientific computing called SCIRun (5,6). For this project, we interfaced SCIRun to a haptic device, and we then used SCIRun to create two displays, one graphic and one haptic, which operate together on a common visualization. The work described here uses the system to interact with vector fields, 3-D volumes in which every point in the volume has a vector associated with it. Examples of vectors are gravity, pressure, force, current, and velocity as well as scalar gradients.

Users of our new system can simultaneously see and feel a vector field. Haptic feedback is displayed on a SensAble PHANToM Classic 1.5 (7). The graphics are displayed on an SGI Octane. The user has a haptic display registered to a graphic display. She directs both displays by moving the PHANToM endpoint through the haptic representation of the data volume. The haptic display presents each vector as a force corresponding to the vector's magnitude and direction. The graphic display presents a subset of the vector field as lit directional line segments (8) or as the traditional arrow glyphs.

This haptic/graphic display is useful for displaying flow fields, vector fields such as fluid flow models for airplane wings in which the vectors tend to align into strong directional paths (9). The haptics feel as if you put your fingertip into a river: the vectors act upon your fingertip, drawing it in the same direction as the local flow field. If the user does not apply any force, the forces displayed onto the PHANToM endpoint naturally draw his finger along the flow lines. This allows the user to trace his finger along the various flow lines within the vector field. The user can also move his finger onto a new path, and again the endpoint begins to follow this new path. This interface allows the vector field to act upon the PHANToM endpoint in a similar manner as a traditional visualization technique called seed point insertion or particle advection (1). The graphical display reinforces the haptic display by showing the endpoint moving along the flow line and by showing the part of the flow line that lies ahead of the current position. The user receives haptic and visual feedback which helps him stay on the path. Figure 1 shows a still image from a user's interaction with a flow line and Figure 2 shows an image of several traced flow lines composited over time.



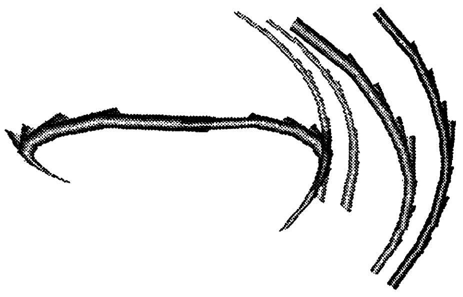


Fig 1 (left). Illustration of user interaction with flow line. The display sweeps out the path to and from the current endpoint position. The pencilled arrow indicates the direction of travel. The sphere represents the current PHANToM endpoint position; the fatter, darker lit lines are the path already taken by the user; the thin, lighter lines are the flow line leading from the current position.
Fig. 2 (right) Illustration of 3 separate flow line traces composited into one image. As the user interrogates the volume, the display forms an image of the flow lines within the field.

System Architecture

Figure 3 shows a high-level view of the software and hardware used for this system.

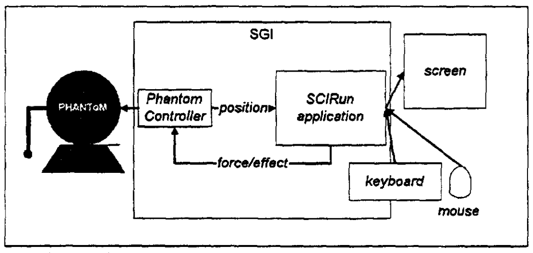


Fig. 3 High level view of system hardware & software

The software runs on an SGI, 02 or better, with a PCI or ISA slot for the PHANToM card.[1] SCIRun and the PHANToM controller are two separate client-server applications (10,11,12,13) which communicate via sockets. The PHANToM controller acts as the server and SCIRun acts as the client. The Appendix contains a full listing of our control loop, written using a small subset of the Ghost SDK. As the size of this listing illustrates, the PHANToM controller is minimal: all the data and computations are handled by the program within SCIRun. Figure 4 shows a dataflow diagram representing the program we wrote within the SCIRun programming environment. The program consists of two loops, the haptic display loop and the graphic display loop. Within the haptic display loop, the program receives the latest PHANToM endpoint position, calculates a force based on that position, and sends out a force to the PHANToM controller. Within the graphic display loop, the program receives the latest PHANToM endpoint position, redraws the endpoint in the graphic display, and recalculates and redraws the vector field display.

[1] Typically we use an SGI Octane with dual 195 MHz R10000 processors, 128 MB memory, and an SGI MXI graphics card.

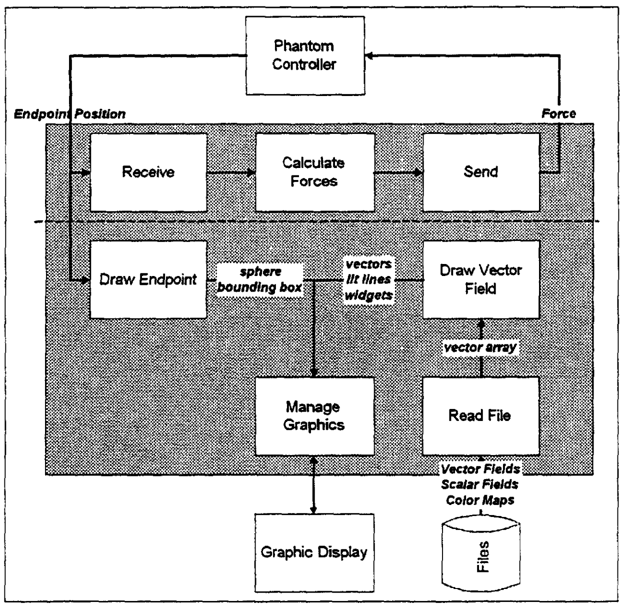


Fig. 4 Dataflow diagram of our software. Each labelled boxes represents a distinct component of the software system. All components within the shaded box run within SCIRun; the rest run outside of the SCIRun runtime environment. The components above the line are particular to the haptic display, while those below are particular to the graphical display.

Future Work

The user can change aspects of the graphic and haptic displays at runtime. One interesting visualization technique we would like to explore is user-defined transfer functions. Rather than mapping data vectors linearly to force vectors, we could map them based on a nonlinear or piecewise linear function defined by the user. Figure 5a) shows an example of a function that could be used to re-map one dimension of the vector field such as magnitude. Vectors with magnitude X along the x-axis are mapped to forces with magnitude Y. The transfer function in Figure 5a) amplifies the effect of small vectors and could be used to fine-tune the display for examining small vectors. The transfer function graphed in Figure 5b) effectively weeds out all vectors in the field except for those within the specified range. If the full range of force magnitudes is used within this smaller data range, then the effect is a haptic "zoom". Note that in 1 dimension, these transfer functions look like traditional force profiles (14) but are data-dependent, not position-dependent.

We also anticipate making use of multiprocessor scheduling on the Octane in order to maintain interactive rates for large visualizations or complex force calculations.

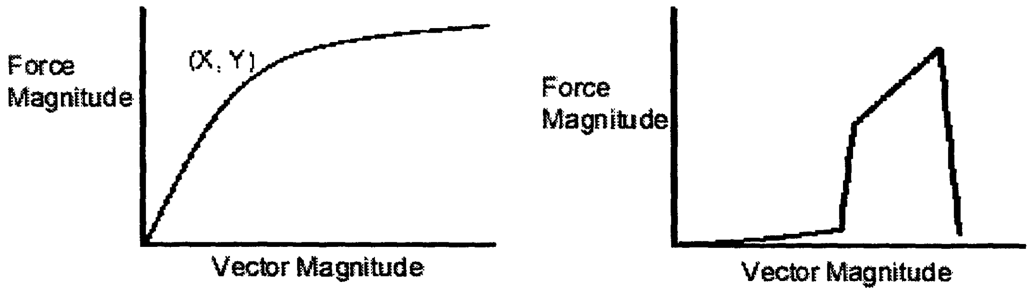


Fig 5a (left), 5b (right). Simple nonlinear transfer functions which map from data vector magnitude to force magnitude.

Acknowledgments

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Appendix: Program Listing for PHANToM Controller

```
// PHANToM_controller.cpp - main loop for PHANToM Controller program
// derived from hello.cpp provided by SensAble
#include <stdlib.h>
#include <gstBasic.h>
#include <gstSphere.h>
#include <gstPHANToM.h>
#include <gstSeparator.h>
#include <gstScene.h>
#include "ljdForceInput.h"
#include "server.c"

main() {
gstScene *scene = new gstScene;
gstSeparator *root = new gstSeparator;

printf("put the PHANToM in neutral position and hit return...\n");
getchar();

gstPHANToM *PHANToM = new gstPHANToM("PHANToM.ini");
root->addChild(PHANToM);
scene->setRoot(root);

ljdForceInput * forces = new ljdForceInput; // force from SCIRun
PHANToM->setEffect(forces);
PHANToM->startEffect();

scene->startServoLoop();
gstPoint pos;  // holds current PHANToM position
double u,v,w;

sock_init();
while (!scene->getDoneServoLoop()) {

   pos = PHANToM->getPosition_WC();
   write_triple(pos.x(), pos.y(), pos.z());   // send position to client, SCIRun
   if (read_triple(&u,&v,&w) == 0) {   // read resulting force from SCIRun
     // copy to readable location
     scirun_force = gstVector(u,v,w);
     // the next time calcEffectForce() happens, it will see this new force.
   }
   else {
     printf("client scirun has shut down.\n");
     sock_deinit();
    }
}
PHANToM->stopEffect(); // quit my force input
}

----------------------------------------------------------------
// ljdForceInput.h derived directly from Ghost SDK CalcEffect.h
#include <math.h>
#include <gstBasic.h>
#include <gstEffect.h>

gstVector scirun_force; // set by main loop

class  ljdForceInput:public gstEffect
{
public:
        ljdForceInput():gstEffect(){} //Constructor
        ~ljdForceInput() {}  // Destructor

        virtual gstVector      calcEffectForce(void *PHANToMN)
            {
                if (PHANToMN);  // To remove compiler warning
                if (!active) return gstVector(0.0, 0.0, 0.0); // check first
                gstPoint pos;
                double xc, yc, zc;  // force vector components
                xc = scirun_force.x(); yc = scirun_force.y(); zc = scirun_force.z();
                return gstVector(xc, yc, zc);
            }
};
```

Haptically Enhanced Molecular Modeling: A Case Study

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INTRODUCTION

SCULPT™ [Surles 92,94] is a commercial, molecular modeling, software application used widely by chemists and biologists to design and analyze molecular structures. SCULPT's main design goal is to reduce the mental energy required to control the human computer interface (HCI), allowing the chemists to instead concentrate on the difficult chemistry issues involved in molecular modeling. Towards this end, SCULPT attempts to emulate the familiar experience of manipulating a physical (i.e. Dreiding) model, allowing users to modify the molecule by grabbing atoms with the mouse and pulling on them. Haptic feedback is a natural expansion to this direct manipulation paradigm, as it allows the user to physically feel both the shape of the molecule and the forces acting upon it. The importance of this is exemplified in docking, which requires accurate positioning of the ligand within the protein receptor site, while constantly monitoring a variety of forces resulting from complex interactions between the ligand and receptor (see Figure 1).

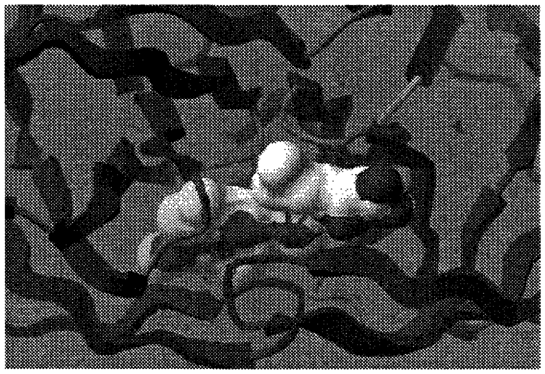

Figure 1: this image of an experimental protease inhibitor (shown as a solvent accessible surface) located in the active site of HIV Protease is indicative of the complex three-dimensional geometries found in docking studies.

We have recently experimented with adding high quality haptic feedback to SCULPT to aid in combinatorial chemistry and rational drug design tasks. This paper describes the implementation using the SensAble Technologies Ghost 2.0 API, and reports on some preliminary results. While the application is specifically geared towards drug discovery, this paper presents a case study that should be generally useful to developers interested in providing haptic support for real-time, dynamic simulations.

ADDING HAPTICS

To keep a structure in a physically valid conformation while it is being modified, SCULPT tightly couples three-dimensional graphics with a proprietary, real-time, energy minimizer. While tugging on an atom, a virtual spring is added between the atom and the cursor. The energy minimization subsequently tries to minimize the length of the spring to reduce the energy in the system. Because the spring is factored in with the other molecular constraints defined on the model, this influences the atom to move towards the cursor without violating the physical constraints of the structure.

Internally, the graphics and user interface are managed by the *Display Manager* and the energy minimization by the *Minimizer*. These two processes communicate through messages over a socket. Haptic rendering is supported by adding the *Haptics Manager*; which communicates via socket with the Display Manager, and is responsible for managing the Ghost scene graph and reporting back changes in the PHANToM state (Figure 2).

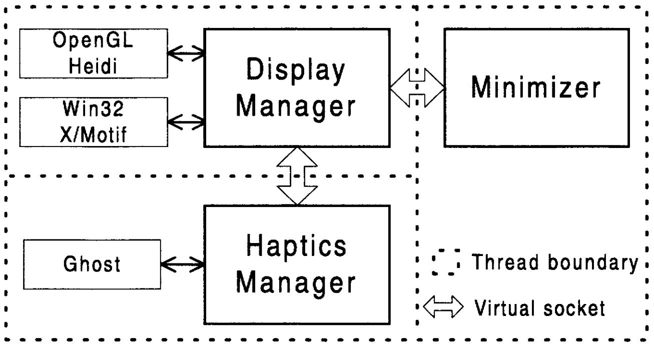

Figure 2: the *Haptic Manager* is added to provide haptic feedback support. It is implemented as a separate thread process that communicates bidirectionally with the Display Manager.

The scene graph used for haptic SCULPT is structured to allow the data to be specified in SCULPT's model space. This is achieved by adding all of the geometry under two, nested transformations (*gstSeparator* nodes). The first transform maps from SCULPT space to PHANToM space, and the second adds the SCULPT camera transform to synchronize the visual and haptic views (see Figure 3). These transforms are kept separately to allow the camera transform to be updated independently when the Haptics Manager receives *Update_view* messages.

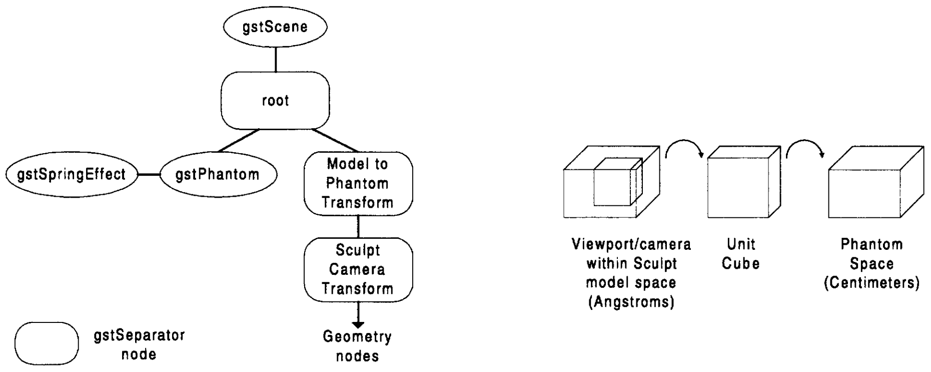
gstScene
root
gstSpringEffect
gstPhantom
Model to Phantom Transform
Sculpt Camera Transform
Geometry nodes
gstSeparator node
Viewport/camera within Sculpt model space (Angstroms)
Unit Cube
Phantom Space (Centimeters)

Figure 3: The scene graph consists of: a *gstPHANToM* node, a *gstSpringEffect* (used for springs), and a sub-graph for the geometry. Two *gstSeparator* transforms are added to allow the coordinates of the geometry to be defined in SCULPT model space. The transformations can be thought of as transforming from SCULPT space to an axis aligned unit cube, then from the unit cube to the PHANToM's space.

The SCULPT to PHANToM space transform can be conceptualized as the concatenation of four transformations. The first translation and scale map from SCULPT space to an axis aligned unit cube, and the second set maps from the unit cube to the PHANToM's space:

Sculpt to phantom transform: = $T_1S_1S_2T_2$, where:

T_1 = translate by (-Sculpt_{xmin}, -Sculpt_{ymin}, Sculpt_{zmin} + Sculpt_{zmax})
S_1 = uniform scale by 1 / (Sculpt_{zmax} - Sculpt_{zmin})
S_2 = uniform scale by $\text{Phantom}_{zmax-zmin}$
T_2 = translate by ($\text{Phantom}_{zmin,}$ $\text{Phantom}_{ymin,}$ $\text{Phantom}_{zmin)}$

There are a couple of nuances to note in this transform. First, transforms S_1 and S_2 use uniform scale factors, as Ghost requires uniform scales within separator transforms. This means that the graphics windows used in the application must maintain the same aspect ratio as used in the boundary cube[1]. Using differing aspect ratios would result in the PHANToM's workspace holding a subset of graphics view, or much it remaining unoccupied. The second nuance leads to the translation by Sculpt_{zmin} + Sculpt_{zmax} in transform T_1. In the SCULPT view model, the front clipping

[1] The Ghost boundary cube is a misnomer as the workspace used often has unequal axis lengths.

plane is always defined at Z=0. This aids in picking and clip plane management, and is required to support graphics APIs, such as Heidi, which cannot render coordinates lying behind the eye point.

Setting the camera transformation is simplified by keeping the individual components of the camera transformation separately, and allows the viewing parameters to be sent to the Haptics Manager. Sending the camera matrix is not possible as it generally contains Ghost hostile, non-affine elements such as perspective projection. The camera transform is:

Sculpt camera transform = $T_wSRT_{COR,}$ where:

T_w = translate by ($-Sculpt_{xmin}$, $-Sculpt_{ymin}$, $-Sculpt_{zmin}$)
R = camera rotation (based on virtual track ball model in Sculpt)
S = uniform scale for zoom factor
T_{cor} = translate by center of rotation ($COR_{X,}$ $COR_{Y,}$ COR_Z)

Defining the transformations in this manner allows all of the geometry to be added in SCULPT model coordinates as child nodes of the camera transform separator. This in turn makes it easy to update coordinates when the energy minimization runs. Updates are performed via *Update_coordinates* messages, which contain an array of updated atom coordinates. An associative array in the Haptics Manager maps SCULPT atom indices to their respective Ghost nodes. Coordinates are then changed on the nodes by calling their *setTranslate* method.

One problem encountered is that the Ghost servo loop timed out when all of the atoms in a complicated protein structure were simultaneously placed in the scene graph. To circumvent this, geometry nodes are created for the entire structure, but only movable atoms ("thawed" in SCULPT) are added to the scene graph. Fixed/frozen atoms lie dormant until a *Change_active_set* message informs the Haptics Manager to add them to the scene graph.

The final node in the scene graph is a spring effect (*gstSpringEffect*) that is attached to the PHANToM and is used to haptically render springs when the user manipulates a structure. This is a custom node that is derived from *gstEffect*. Unfortunately, a *gstConstraint* point effect cannot be used as the force phase-in timer is restarted everytime the fixed point is moved (i.e. the atoms coordinate changes). When a tug is started the spring effect is turned on, with the fixed end of the spring attached to the center of the atoms being dragged. The force vector lies on the vector from the atom center to the cursor, with a magnitude determined by Hooke's law.

When not processing incoming messages, the Haptics Manager informs the Display Manager of changes in the PHANToM end effector position and stylus button state. Positional and orientational information is used to update the 3D cursor, and button changes to grab and release atoms. To prevent the Haptics Manager from flooding the display side with messages, PHANToM state changes are only reported when the stylus button state is changed, or the end effector position changes in excess of a delta factor.

When the stylus button is pressed the Display Manager determines if an object is within the pick radius of the end effector. Successful picks are relayed to the Haptics Manager, which turns on the spring effect. The Haptics Manager also calls *touchableByPHANToM* on the model to phantom transform separator, making the geometry sub-graph untouchable. This speeds execution of the servo loop and allows the spring to move freely without colliding with the geometry. Both of these operations are then reversed when the stylus button is released.

RESULTS

While we are still early in the implementation of Haptic SCULPT, several chemists have tested the prototype. We plan to perform formal user studies when the system has matured, but for now the results are based on informal comments made by users during and after haptic modeling sessions involving three common modeling tasks.

1. Analysis of conformational flexibility: Assessment of the flexibility of small molecules by interactively exploring the resistance required to rotate bond angles and the strain energy required to match a known conformer.
2. Exploration of surfaces and properties: Exploration of the distribution of properties on a structure. This is currently limited to feeling the three-dimensional shape formed by the intersecting electron shells (i.e. a CPK model).

3. Interactive docking: Interactive guiding of a ligand into a receptor site, while haptically reflecting the forces acting on the ligand. The current version does not support rotating the ligand.

All of the tests were met with extreme enthusiasm, with users commenting that the PHANToM provided a natural and highly functional interface. The general consensus was that haptic feedback was intriguing, but the update rate needed to be increased before it would significantly enhance modeling. This was due to a choppy, "ratcheting" effect that was felt as the fixed spring point was updated in sync with the minimizer at approximately 3 Hertz. This result is supported by the literature, which suggests update rates in excess of 30 Hertz are needed to provide high quality sensation of springs. We were able to eliminate the ratcheting sensation by loosening the spring constant, however doing so made it difficult to feel forces acting on the structure. Users also noted that docking requires the ability to rotate the ligand to be useful, and that six-degree of freedom haptic output is also desired to feel torsions acting on the structure.

Several users were able to contrast Haptic SCULPT to the haptic docking experiments performed as part of the GRIP project at the University of North Carolina at Chapel Hill [Ouh-Young-90]. Several distinct advantages were noted. The PHANToM hardware provides improved ergonomics and a significant reduction in cost compared to GRIP's Argonne arm. Users were also quite impressed with the speeds achieved by SCULPT on a Pentium II class PC, and liked the ability to perform flexible docking and the ability to use the mouse and PHANToM simultaneously.

FUTURE WORK

There are two main areas being examined for future work. First, is to improve the saliency of the haptic feedback. To do so we are looking at several ways to increase the haptic update rate. While the cursor can be drawn in overlay planes on top of the scene in the mouse driven version, the true 3D nature of the PHANToM requires the full scene to be redrawn to reflect cursor movements. We hope to reduce this bottleneck by only redrawing the image region underneath the cursor when nothing else changes. This can be done by saving the image region underneath the cursor before it is drawn, and restoring it before updating the cursor. The second technique is to linearly interpolate the fixed spring point position in between simulation updates as was done in the nano-manipulator project [Taylor-96].

Other future work involves improvements to the functionality of the system. Beyond the problem areas mentioned by users (such as changing orientation), there are a large number of interesting avenues to pursue in this relatively unexplored application area. Two interesting examples are: haptically rendering attractions and repulsions of field properties surrounding structures (e.g. charge), and adding haptic support for de novo design of proteins. For the latter, it would be interesting to make large scale structural changes by directly tugging on secondary structures.

ACKNOWLEDGMENTS

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Incorporating Haptics into Mining Industry Applications

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Abstract

This paper describes how we are incorporating haptics into geoscientific applications. These applications involve the creation and modification of complex 3D structural geological models. Current commercial software tends to use 2D displays, which limits the scope for effective visualisation and, in particular, effective interaction with models of realistic complexity. The use of the Haptic Workbench in these tasks improves both the quality of the visualisation and of the interaction with the models. The Haptic Workbench consists of a small-scale immersive virtual environment (a Virtual Workbench) and a co-located PHANToM 1.5.

We describe a typical 3D geological modelling task that occurs in the metalliferous mining industry. We show how hapto-visual techniques can make a substantial improvement to the task and how they are very dependent on the development of both good data representations and translators from existing data formats produced by commercial software packages.

1. Introduction

Haptic interaction has a major role in future mining industry applications involving such interactive tasks as minerals exploration, geological and ore-body modelling, mine planning and mine production management. The fundamental task is that of constructing models and testing hypotheses in a three-dimensional earth-modelling framework. In this framework, haptic interaction will allow both haptic rendering of data and haptic assistance with ergonomics.

Our work towards incorporating haptics into mining industry applications combines two strands:

- Experiments with 3D co-located haptics and graphics, and placing the resulting prototypes in use at a mine site
- Object-oriented software development to support the entities required for the next generation of mining applications

The experiments combined a PHANToM 1.5 haptic device with the Virtual Workbench small-scale immersive virtual environment from what is now Kent Ridge Digital Laboratories in Singapore [Poston-94] and resulted in a demonstration suite which was presented at SIGGRAPH'97 as part of SensAble Technologies' booth. We are calling the result of this integration of haptic and visual displays the Haptic Workbench. These experiments were conducted as part of a collaborative project within the Advanced Computational Systems Cooperative Research Centre [http:acsys.anu.edu.au] with three companies from the mining industry as partners. The experiments showed that immersive Virtual Environment systems using haptic interaction offer major benefits in this industry.

2. The Target Mining Application

We chose as our first application the task of modelling geological surfaces – ore-body envelopes, contacts between different rock types and fault planes. The task has three phases:

- Collecting field data (from drillhole logs, mine workings, geophysical surveys) and fusing the data to form a 3D modelling context
- Performing the modelling task by constructing surfaces in the 3D space to represent geological features (both constructing new models and editing existing ones)
- Using these models for decision making in mine management.

The second phase is the focus of our work; the first and third phases are covered by existing software. We aim to provide hard and soft constraints using both visual and haptic media to assist the geologist. At the heart of the task is building a triangulated surface that passes through known points on drillholes, or known lines on the sides of the mine workings. Since the data points are sparse and sometimes unreliable, we need to hapticly render soft constraints so that a geologist can apply his or her expert knowledge to the surface modelling task. We are working with two Australian mining industry companies, WMC Resources Ltd and Fractal Graphics Pty Ltd, to set the requirements for this work and to review successive prototypes. We are placing a Haptic Workbench at a mine site in Kambalda, Western Australia, where the prototypes will be used to do real application tasks.

3. Building Blocks for Geoscientific Applications

3.1 The Haptic Workbench

Haptic interaction with data requires a method of integrating the user, the haptic device and the application context. We provide this integration with our "Haptic Workbench" which is a small-scale immersive virtual environment combining co-located graphics and haptics. The Haptic Workbench is based on a "hands in" interaction paradigm where the user sits at the workbench and uses virtual tools to do work with objects and data in the display [Stevenson-99].

Writing applications for the Haptic Workbench requires a scenegraph based programming interface that handles haptics and graphics in a unified manner. Work towards such a programming interface is being done jointly by ACSys and ReachIn Technologies AB [http://www.reachin.se]. Work towards this mining application draws on successive prototypes of this programming interface.

3.2 CSIRO DataModel and GeoEditor

To bring a new technology like haptics to an application domain, a programmer needs high-level programming support for the underlying data and attributes inherent in that domain. For our geological applications, the CSIRO DataModel and GeoEditor for 3D geoscientific data provides that support [Power-95, Lin-95]. CSIRO has been working since 1992 on software infrastructure to support the next generation of geological software applications and the "DataModel" and "GeoEditor" are some of the results. The DataModel is a set of C++ class libraries to support the 3-dimensional geometry and topology needed to describe geological entities. The GeoEditor is an application framework built on the DataModel. It provides support for generalised attribute handling including storage of attributes and their mapping to a range of visual representations and is designed to handle the wide variety of information required in a geological application.

3.3 CSIRO DataTranslator

Our approach to using haptics for mining applications has been to target niche activities that benefit from haptic interaction and to rely on existing or legacy software to support the other components of the broader task. We needed the ability to import and export data and attributes from a range of software systems so that our niche applications would slot cleanly into the workflow currently used in the mining industry. The CSIRO Data Translator provides this facility. An extension of the GeoEditor framework, the Data Translator is itself a programming framework and we are using it as the starting point for our development work.

3.4 Wavelet Technologies

Wavelet-based subdivision of a triangulated surface provides the secondary mesh points within larger triangles to support geological interpolation between data points and change-of-scale editing. The required wavelet toolkit has been developed within ACSys in response to the need for such features in our application prototypes. [Stollnitz-97]. We expect wavelets to assist in two areas. Change-of-scale surface editing allows the user to sketch in a coarse triangulation of a surface, then progressively refine the triangulation [either point by point or with some haptic deformation tool] as more detail becomes available. The user can also revert to the coarser triangulations to correct initial errors without losing the fine detail. Change-of-scale display allows the software to decide on an appropriate level of detail for display. This might involve culling features that are sub-pixel in display size, or it might involve reducing the graphics load for rotating, moving or animating the displayed objects.

4. Haptics in a Geological Modelling Environment

4.1 General ergonomic benefits of haptics co-located with graphics

These benefits apply widely and are not unique to geological applications. The value of co-located haptics and graphics, as against graphics alone, is strongly seen in two features:

- Haptic interaction is effectively instantaneous, allowing the user to move at normal human speeds rather than the slow actions needed when relying on graphical feedback
- Haptic displays are read directly by the finger, hand and arm muscle receptors (rather than via the visual pathway and the conscious part of the brain) which leads to a strikingly realistic perception of the objects in the scene.

In our geological modelling task, the 3D metaphor of virtual environments translates directly to 3D models of underground geology and the illusion of 3D reality strongly enhances the user's understanding of the geological scene.

4.2 Specific geological haptic metaphors

In his use of haptics (via the Haptic Workbench) in interpreting 3D seismic oil exploration data McLaughlin [McLaughlin-97] showed the importance of getting a good match between haptic properties of objects and meanings that those objects have for experts in a particular discipline or application. We face a similar problem with our chosen geological application, and are focusing on the following haptic metaphors.

Surface deformation

We have demonstrated using a haptic tool with variable radius of curvature to deform a surface, where the surface is made up of finely sub-divided triangles, as if moulding a thin sheet of deformable material. The user can feel the surface resisting being deformed, and can use this haptic feedback to guide very fine modifications to the surface's shape.

Attraction to drillholes and to lithology boundaries

Two basic tasks in building geological models are identifying lithology boundaries on drillholes and joining up contact points from drillhole to drillhole to form sparse triangulated surfaces. We can allowing the haptic stylus to be attracted to a drillhole then move freely along the line of the hole while the user selects locations for contact points. We can also allow the haptic stylus to be drawn towards a contact point. Both assist the user to do the modelling task.

Attraction to a surface

We are experimenting with attracting the haptic stylus to a surface, so that the stylus is free to move over the surface but resists being taken off the surface. This type of surface movement constraint will allow geologists to work easily on a selected surface without the physical and mental effort of keeping an otherwise unconstrained stylus located in 3-space. An example would be marking the line where two geological contact surfaces meet to bound a rock type that has "pinched out".

5. Conclusions

We have described the process of incorporating haptics into an industrial application, in this case geological interpretation for minerals exploration and mining. We have shown how this required:

- An existing industrial process which was well supported by domain-specific software libraries
- A niche activity in the application with a focus on 3D interaction
- Software support for import/export to connect the niche activity to the existing application
- Committed industrial partners to help with specifications and field-testing.

The niche activity must have concepts and data in the problem domain that map well onto 3D haptic interaction. We chose an application where both the data items and concepts/models actually exist in real life as 3D objects. This assisted the process of designing haptic attributes and haptic interactions.

Finally, we conclude that it is very important to have co-located graphical representation of the entities in the application. The graphic and haptic displays reinforce each other in the mind of the user, leading to successful application development.

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The Role of Haptic Communication in Shared Virtual Environments

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Abstract

We are conducting a set of human experiments to investigate the role of haptics in shared virtual environments (SVEs). Our efforts are aimed at exploring (1) whether haptic communication through force feedback can facilitate a sense of togetherness between two people at different locations while interacting with each other in SVEs, (2) what types of haptic communication/negotiation strategies they follow, and (3) if gender, personality, or emotional experiences of users can affect the haptic communication in SVEs. In general, the experiments concern a scenario where two people, at remote sites, co-operate to perform a joint task or play a game in a SVE. The experiments are abstractions from real situations in order to create a more controlled environment suitable for experimental studies in the laboratory. This paper discusses the design specifications of three experiments and presents the results of one of the experiments. Initial results suggest that haptic feedback significantly contributes to the feeling of "sense of togetherness" in SVEs.

1. Introduction

Investigating the sense of being and collaborating with someone in shared environments has become an increasingly interesting research topic for engineers, computer and cognitive scientists, and psychologists who conduct research in the areas of virtual reality, teleoperators, and human-machine interfaces. Although there have been several studies recently focused on development of multisensory virtual environments (VEs) to study presence, little attention has been paid to co-presence, that is the sense that participants have of being and interacting with each other. Furthermore, to our knowledge, no attention paid at all to what extent the addition of touch and force-feedback between people would contribute to the shared experience.

In the past few years, we have developed rendering techniques for multimodal VEs that include visual and auditory displays together with haptic interactions (reviewed in Srinivasan and Basdogan, 1997). Recently, we used our VE set-up for performing a set of human experiments to study whether haptic communication through force feedback has any influence on the sense of togetherness between two people. To assess the effect of haptic cues on the sense of being together in VEs, we use performance as well as subjective measures (Ho et al., 1998; Durlach and Slater, 1998).

The results of the proposed experiments will enable us to understand the impact of force feedback (1) on the performance of the task, (2) on the sense of being together as reported by the participants, and (3) on the extent to which participants can identify the *personality characteristics* and *emotional feelings* of each other based on what they could feel in shared virtual environments. The outcomes of this research can have an impact on the development of next generation human-computer interfaces and network protocols that integrates touch and force feedback technology into the internet; development of protocols and techniques for collaborative teleoperation such as hazardous material removal, space station repair, and remote surgery; new telecommunication devices and enhancement of virtual environments for performing collaborative tasks in networked shared virtual worlds such as co-operative training, planning and design, cyber games, and social gatherings.

2. Design and Implementation of Experiments

We have designed three different experiments involving co-operative manipulation, navigation, and game playing to investigate the role of haptic communication in SVEs. This section describes the protocol and design of each experiment. At the time of writing, we have completed the design and implementation of all the experiments. We report here only the results of one experiment.

A) Experimental protocol and conditions

During each experiment, subjects were asked to perform a collaborative task in a SVE. Subjects were not allowed to meet their remote partner, and did not know where their partner was located. The participants were in different rooms but saw the same visual scene on their monitor and felt the objects in the scene via a force feedback device, the PHANToM (Figure 1).

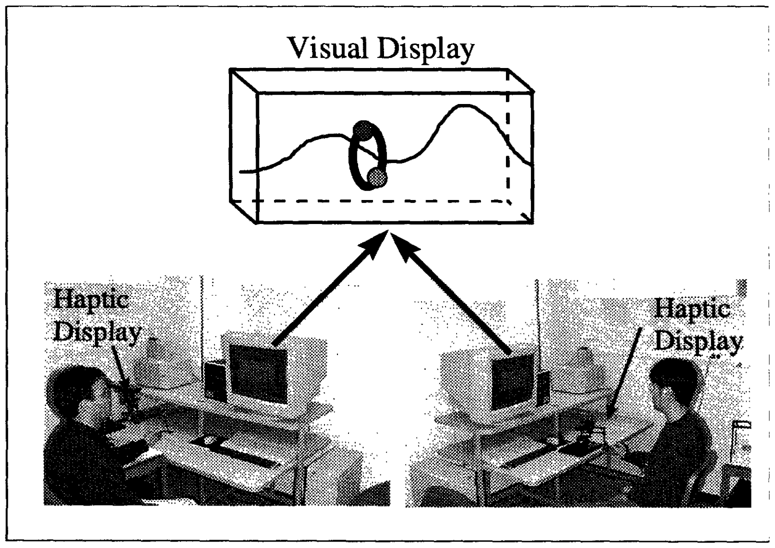


Figure 1. Our VR set-up enables two people at remote locations interact with each other through visual and haptic displays. For example, subjects can hold and move a ring on a wire in a collaborative manner as depicted in this figure.

The shared visual scene depended on the type of experiment. Three different types of experiments have been designed to be conducted. Two sensory conditions have been explored to investigate the effect of haptic communication on the sense of togetherness:

(a) both visual and haptic feedback provided to the participants

(b) only visual feedback was provided to the participants

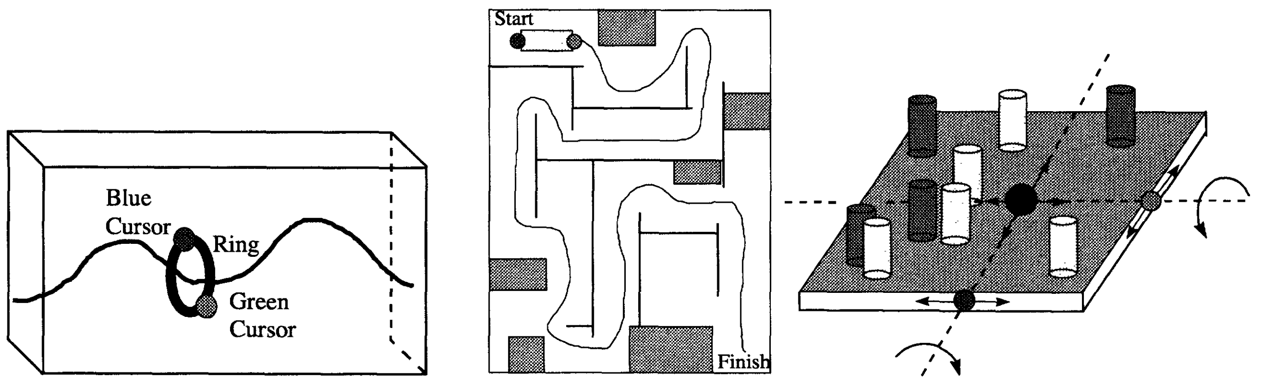
Short description of each experiment and its protocol are provided in the next section. In general, when the subject manipulates the stylus of the PHANToM with his/her right hand, a cursor moves in 3D space, so that the controlled object translates or rotates depending on the task. In particular, the following set of collaborative tasks was designed to study the effect of haptic interaction in shared virtual environments.

B) Description of experiments

1. *Move the ring on a wire*: The goal of this task is to move a ring with the help of another person without touching a wire (see Figure 1). A ring, a wire, and two cursors (green and blue small spheres that represent the contact points of each subject) attached to the ring were displayed to the subjects (Figure 2a). Haptic interactions between cursors as well as between cursor and the ring were modeled using a spring-damper system and a point-

based haptic rendering technique (Ho et al., 1997 and 1998). Subjects were asked to move the ring back and forth on the wire many times, in collaboration with each other such that contact between the wire and the ring was minimized or avoided. If the ring touched the wire, the colors of the ring and the surrounding walls were changed to red to warn the subject of an error. They were changed back to their original colors when the subjects corrected the position of the ring. To hold the ring, both subjects needed to press on the ring towards each other above a threshold force (see Figure 2a). If they did not press on the ring at the same time, the ring did not move and its color was changed to gray to warn them. To move the ring along the wire, they each needed to apply an additional lateral force.

2. *Navigate in a maze*: The goal of this task is to move a rectangular block inside a maze with the help of the other person without touching the walls of the maze (see Figure 2b). The block was modeled as a line segment and the ray-based haptic rendering technique was utilized to detect the collisions with the walls of the maze (Basdogan et al., 1997). If the block touched a wall, the scene color was changed to red to warn the subject of an error. It returned to the original color when the subjects corrected the position of the block. To translate the block inside the maze, subjects needed to push and pull the block in a collaborative manner. They needed to apply lateral forces to rotate the block while turning the corners.
3. *Tilt the board*: The goal of this task is to control the orientation of a rectangular board with the help of the other person in order to make the ball, initially located in the center of the board, roll and touch all the light colored cylinders, but avoid contact with the dark ones (see Figure 2c). Each subject could tilt the board in only one direction via the use of PHANToM.



(a) (b) (c)

Figure 2. Experimental designs: **(a)** Move the ring on a wire **(b)** Navigate in a maze **(c)** Tilt the board.

3. Development of measures and analysis of data

Our aim was to understand the effect of haptic cues on the sense of being together in VEs using *performance* and *subjective* measures. Subjective measures were correlated with performance measures to quantify the role of haptic communication in SVEs.

A) Performance Measures

A *performance* measure (e.g. score) for the "sense of togetherness" was derived from the following measurements: (1) total amount time takes to complete task (2) number of times subjects made errors (error is defined slightly different for each experiment: error occurs when the ring touches the wire in experiment 1, when the block touches the walls of the maze in experiment 2, and when the ball hits the red cylinders in experiment 3) (3) the ratio of erroneous-time to total time (for experiment 3, this is the ratio of number of times the ball hits the red cylinder to the total number of cylinders).

B) Subjective Measures

After each experiment, each subject answered a questionnaire, which supplied basic demographic and background information. Several *subjective* questions were asked in four categories including their (1) performance, (2) their sense of 'being together', (3) emotional reactions, and (4) personality profile. Each of the questions in categories 1,2, and 3 were rated on a 1-7 scale. This is in line with rating system used in previous studies of presence (Slater and Wilbur, 1997).

Results

We present the results of the first experiment (i.e. Move the ring on a wire). All the subjects played the game with one of the experimenters who was an "expert" player. Two separate groups of subjects, total of 10, participated to the experiment. The subjects in Group I (5 naive subjects) received first visual and haptic (Condition 1), and then later visual only (Condition 2) feedback. The subjects in Group II (5 naive subjects) received first visual only feedback and then later visual and haptic feedback. Subjects repeated the same task at least 10 times for each experimental condition. For each trial, the performance of the subject was recorded to generate a performance score. An overall performance score was obtained for each subject by averaging the scores obtained for each trial. Subjects were also asked to complete a subjective questionnaire for each experimental condition tested. There were seven questions that related to the sense of togetherness experienced. The subjective level of togetherness experienced by a player was computed by averaging the responses given to seven different questions. A plot of this averaged subjective sense of togetherness against the averaged performance score realized in the game is shown in Figure 3 for the subjects in group I and group II. It can be observed from the plot that there is a direct correlation between the subject's performance and his/her subjective sense of togetherness. Moreover, haptic plus visual condition results in a higher sense of reported togetherness than the visual only condition based on our measurement system (see Figure 4).

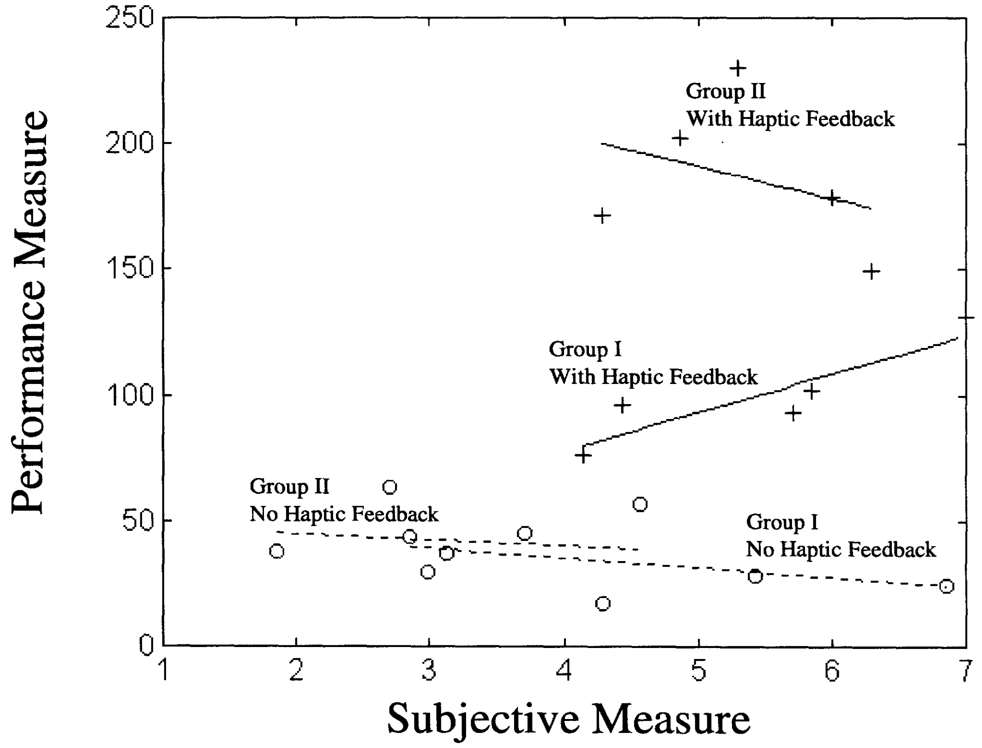
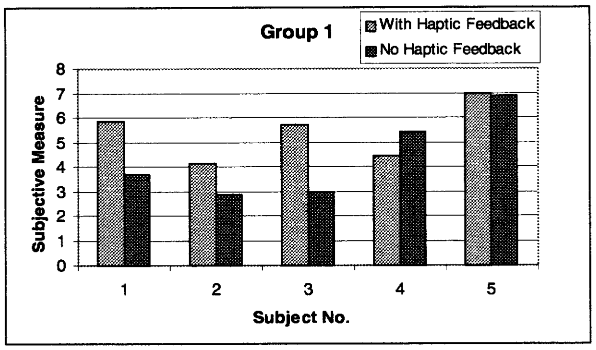
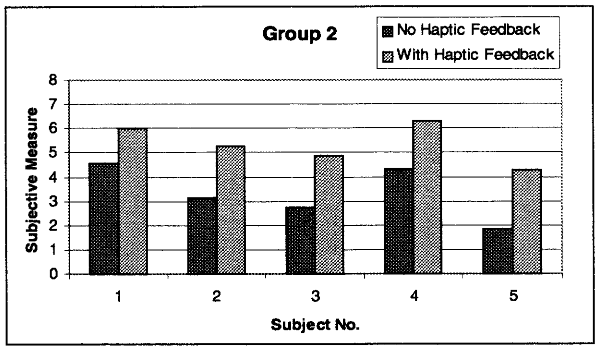


Figure 3. The Y-axis shows the average performance score achieved by a player during the trials. The score was based on the number and proportion of contact times between the ring and the wire. The X-axis shows the average subjective score of a player based on the seven 'togetherness' questions.





(a) **(b)**

Figure 4. Subjective scores (i.e. score for "sense of togetherness") of each subject in groups I and II are represented as bar charts for comparison of experimental conditions (condition 1 vs. condition 2). Results show that subjective sense of togetherness increases in all subjects, except one, with the addition of haptic feedback.

Conclusions

This papers reports the results of ongoing experiments to examine the extent to which haptic communication, in addition to the usual visual feedback, influences the sense of togetherness between remote participants in a SVE. The results obtained suggest that haptic feedback adds significantly to the sense of togetherness. There is also a clear influence of haptic feedback on the performance of the task. More experimental studies, including experiments 2 and 3, will be conducted to further investigate the role of haptic feedback in SVEs.

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"A PROJECT TO STUDY HUMAN MOTOR SYSTEM"

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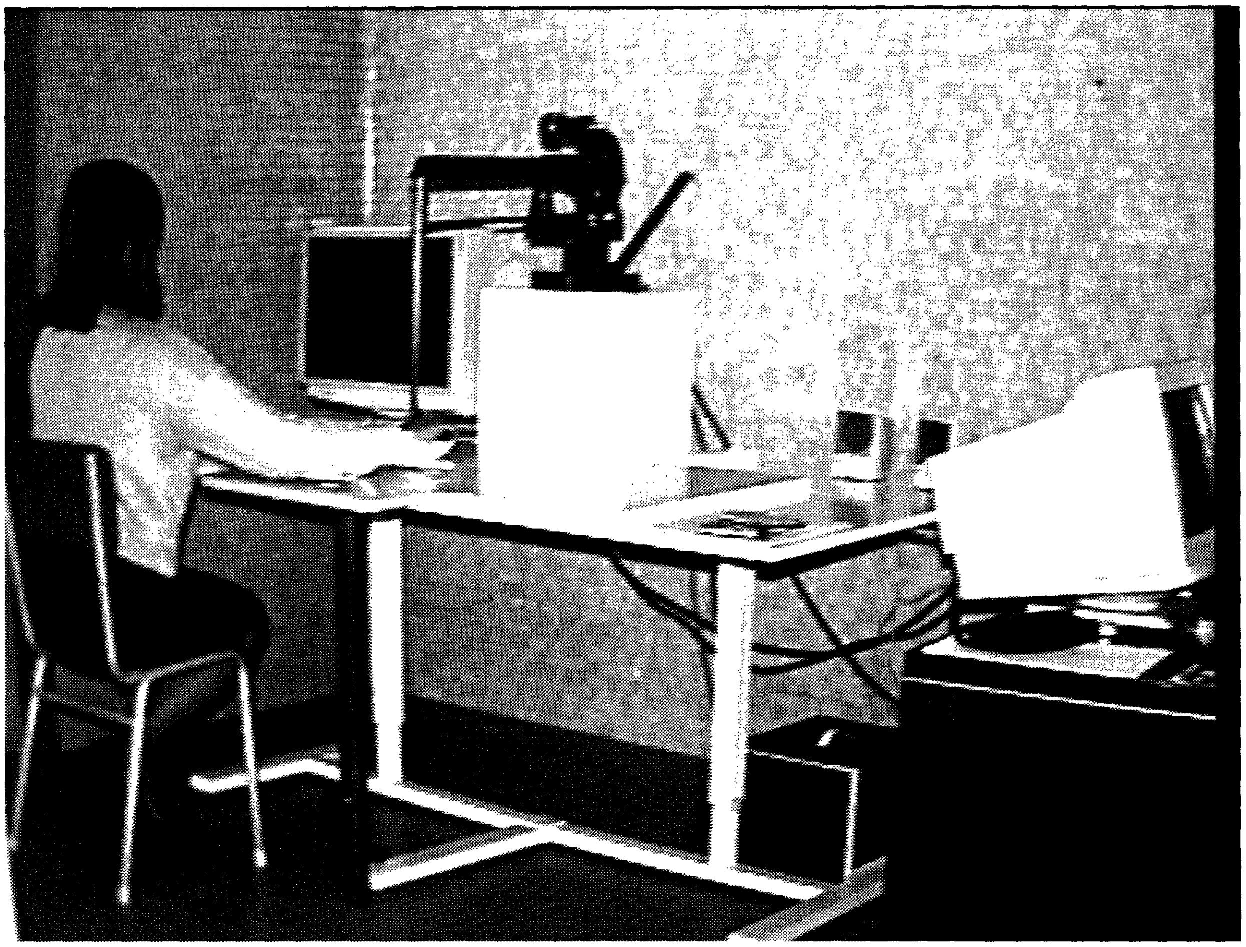
Introduction

An essential ability of the human motor system is to learn new movement sequences to adapt to external environments.
Previous studies have shown how young subjects adapt to external forces perturbing the motion of their arms [1,2,3]. The subjects learned quickly how to compensate the displacement of their arms caused by the perturbing forces.
This learning was localized at the specific positions where the forces were applied and decayed smoothly with the distance from these positions, suggesting a local model of adaptation. However motor learning may decline with increasing age, as it has been demonstrated for other cognitive domains. The characterization of the motor function in elderly may have some therapeutic implications; for instance it may help to plan scientifically based rehabilitation programs for aged people with motor impairments due to brain lesions such as stroke.
Along this line we designed a study protocol for identifying motor learning and motor control features in normal subjects over fifty years old, using Phantom 3.0 Robot (Sensable Technologies). Our experimental procedure was similar to the one used by Shadmehr et al., Gandolfo et al. at M.I.T. for testing young people [1,2].

Apparatus

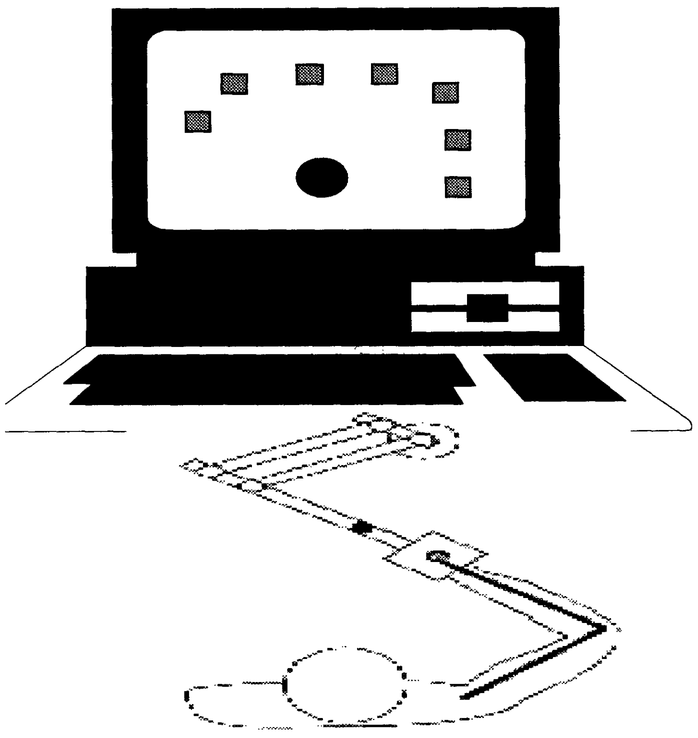
The experimental setup is shown in the figure below.



Subjects are seated in front of a computer screen placed upon a wooden table, the high of which is adjustable in order to provide the most comfortable setup. A special kind of thick Teflon was glued on the top of the table to obtain a very slippery surface. Furthermore, the subject's arm is positioned in a thermoplastic support, which slides very well on Teflon with a minimum degree of viscosity. Subjects are grasping the stylus of a manipulandum (Phantom Robot) which can be freely moved in any direction of the surface of the table. The stylus is equipped with thermic sensors (safety switch) so that when the surface temperature drops suddenly, as when the subject leave the stylus, the apparatus turns off. The trajectories produced by the subject are visualized on the computer screen. The operator can follow the task in the connected PC computer (Pentium Intel II 200 Mhz), which records the motor performances. In addition he has a safety switch to interrupt the task whenever is required.
A Visual C++ program, working on Windows NT Platform, controls the system.

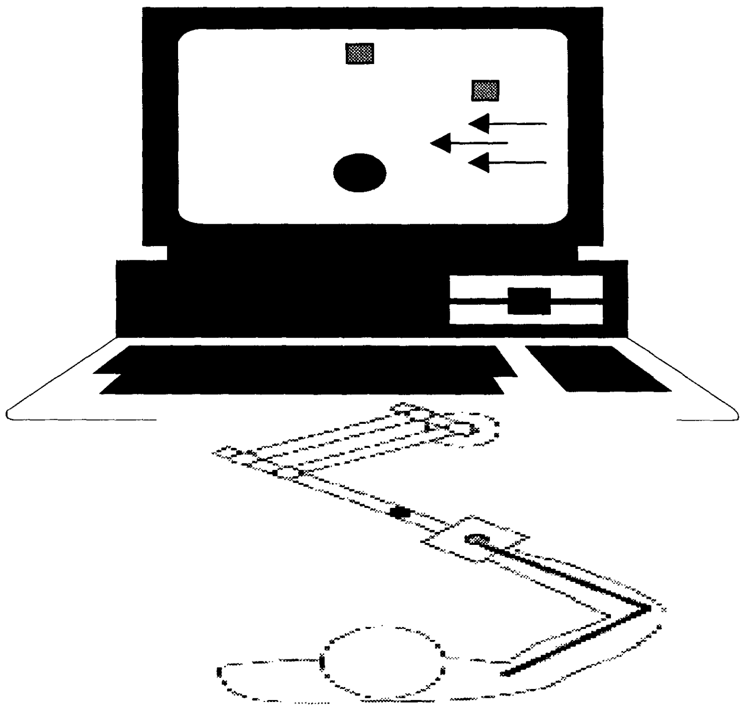
Task

At the beginning the subject is required to set the stylus in a position corresponding to the starting point (black circle in the Figures) located in the workspace of the computer screen.



Training session.

Subjects have to reach, moving the manipulandum, a squared target (grey in the Figure), which randomly appears on the screen in 1 of the 7 prefixed positions, within 500 ± 50 ms. Visual and auditory feedback are provided: when the movement is too fast the target turns red, when it is too slow the target turns blue and when it is within the time range the target blows-up and a sound is heard. The training session comprises 300 reaching movements. At the end of the session subjects have learned to perform the task at the prefixed speed.



Learning session

Only two target positions are tested in this session (at 0° and 45° in respect to the subject). A velocity proportional perturbation (arrows in the figure) is applied through the robot. With time, subjects learn to compensate the external perturbation and to reach the target within the prefixed time (500±50 ms). The initial distorted trajectories resume the prototypical straight shape. This session consists of 500 trials.

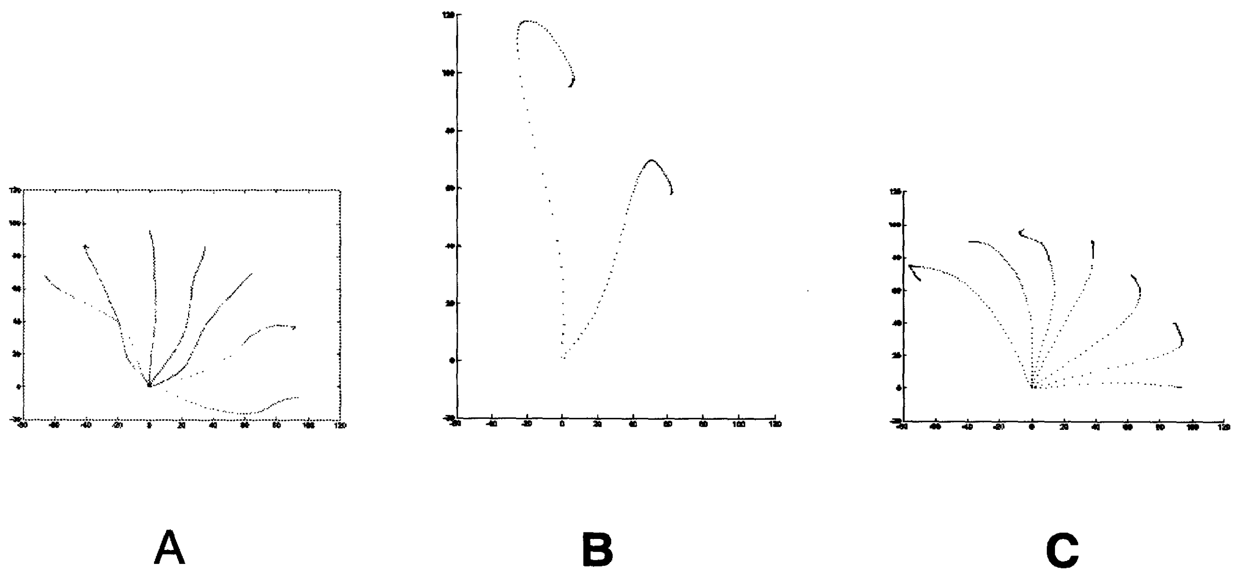
Testing session

Once learning is again accomplished, a third set of 200 trials are administered. All the target positions used during the training session are tested. In this session we study the effects of force field removal on motor performance.

Results

We have tested 18 over fifty year old subjects and five young volonteers, ranging in age from 16 to 35 years. No adverse reactions to the experimental procedure were registered.

The figure shows the typical straigth shape trajectories of the reaching movements to visual targets during the training session (A), the trajectories distorted by the force field applied, when the subjects is still unable to compensate the perturbation (B), and the aftereffects once the perturbation is removed (C). The aftereffects are the mirror images of the trajectories observed at the beginning of force field exposition. Notice that the aftereffects are more evident in the two position where the force field was applied (position 0° and 45°), while it is minimal at 90°.



Conclusions

Our data in young people are in agreement with the results obtained in the previous study with a different apparatus. Therefore, we believe that the Phantom is a reliable and safe tool for studying motor system function in humans.

In the 18 subjects over fifty, there is evidence of force compensation learning. In fact they are able to perform nearly straight trajectories under force field perturbation. In addition, we have found that the magnitude of the aftereffects decreases with the distance from the positions that experienced the force perturbations, suggesting the persistence of a local model of adaptation in elderly.

However, some subjects have a big latency in learning the baseline of the task (reaching the target within the required time). In addition old subjects seem to learn force compensation less quickly than younger people do and the aftereffects persist for a longer time. These data may indicate that some alterations in the mechanisms of motor learning take place with advancing age.

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VISUALLY IMPAIRED PERSONS' USE OF THE PHANToM FOR INFORMATION ABOUT TEXTURE AND 3D FORM OF VIRTUAL OBJECTS

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Abstract

The experiments reported are part of a series of studies aiming to investigate the potentials of a force feedback device such as the PHANToM to solve visually impaired people's problem of getting effective and easily read depictions, including 3D scenes. It was shown that the roughness of virtual textures and the 3D form of simple objects could be judged without visual guidance. An experiment with visually impaired observers indicated that many of them can perform on a similar level as blindfolded sighted observers, but that some of them have problems in performing the task. On-going experiments investigate if these problems can be solved by extra training in method of exploration.

The PHANToM Used Without Visual Information

A main problem concerning depictions for the visually impaired is that it is often very difficult to perceive 3D aspects of 2D tactile pictures (cf. Jansson, 1988). A display providing easy access to these aspects would mean an important breakthrough. The haptic force feedback displays, such as the PHANToM, provide potentially a solution to this problem.

However, even if virtual 3D objects are certainly rendered by the PHANToM, it has to be proved that the information presented can be utilized by the users, in the present case visually impaired users. A general problem is that the PHANToM virtual objects can not be explored in the same way as real objects. Normally, sufficiently small objects are manipulated by the observer holding them with both hands using several fingers. For exploration with the PHANToM there is never more than one point of contact between the observer and the object at a time. This point of contact, whether within a "thimble" or at the end of a stylus, is located differently from any of the natural contact points between observer and a real object. The problems these special ways of exploring may cause might be enhanced when vision is not available, as haptics in this case is deprived of the normally close cooperation between vision and haptics (cf. Heller, 1982). This means, for instance, that a visually impaired person has problems with getting an overview of a scene and finding its relevant parts.

Another potential problem is that a virtual haptic object is not an exact copy of a corresponding real object. The differences may not be important, but it can not be known for sure, especially not if they can not be compensated for by visual information.

The present paper is one in a series intending to study the usefulness of the PHANToM for depicting virtual scenes without vision being involved. Studies on two aspects basic for haptic perception, texture and 3D form of objects, are reported.

Experiment 1. Perceived Roughness of Real and Virtual Sandpapers

Haptics is very accurate in discriminating and identifying textures, sometimes better than vision. The physical properties of textures may be very complex and difficult to reproduce for virtual textures. Green & Salisbury (1997) developed a method to acquire data about the physical properties of textures with the help of the PHANToM by registering lateral forces and the z position of the endpoint of a stylus when it is moved over the surface. The virtual surfaces are based on parameters from these measurements. They are not exact copies of the physical surfaces but the intention is that they should be sufficient for accurate perception of the textures.

The aim of the experiment, described in more detail in Jansson (1998), was to compare corresponding real and virtual sandpapers rendered by a PHANToM 1.5A with the Green & Salisbury method. Twelve paid sighted blind-folded university students explored the two kinds of sandpaper with a stylus and made magnitude estimations of the roughness of sandpapers with four different degrees of physical coarseness. Their judgments were based on haptics alone, the auditory information being masked.

The result was that corresponding real and virtual sandpapers were judged to have very similar degrees of roughness. There was a tendency for the virtual sandpapers to be judged as somewhat rougher than the real ones, but the difference was not statistically significant.

Experiment 2. Identification of 3D Virtual Geometric Forms

A necessary prerequisite for a haptic display to be useful for visually impaired people is that the form of objects can be identified without visual guidance. The aim of this experiment was to investigate to what extent objects of some 3D geometric forms of different sizes could be identified when rendered with the PHANToM.

The preparation of the series of experiments required the development of a model editor that allowed easy creation of virtual 3D scenes. As the import of OpenInventor models is possible but haptic parameters like friction are not included within these models, it proved necessary to develop a new system which was named ENCHANTER (see Fig. 1).

ENCHANTER – An ENvironment for Creation and HANdling of Tactile ExpeRiments

The main purpose of ENCHANTER is the insertion and the manipulation of primitive objects. In addition, it makes possible the combination of different scenes for experiments. The PHANToM is used as an input device for the model editor. One task it is well-suited for is the transformation of haptic objects using the gstManipulator classes provided by the GHOST SDK. Object picking in 3D scenes is also very easy to perform with the PHANToM's help. In the ENCHANTER you simply tap an object to select it, another tap will deselect it. In contrast to mouse selection, this method allows a far more natural way of interacting, especially because the user feels the object while selecting it. Another aspect is that mouse selection is limited to objects visible on the screen, whereas the PHANToM can be used to select all objects in the 3D environment resulting in higher precision and speed.

Even if it was not utilized in the present experiment, it may be mentioned that several regular textures (sinus, triangular and rectangular), as well as textures produced by other software programs, can be rendered with ENCHANTER. The texture mapper was extended to make these textures available to all haptic objects, of any form, provided by the GHOST SDK. This was done by introducing an effect class, making it possible to adjust the force normals returned from a collision detection. Using this, it is only necessary to subclass the shape in order to introduce data members for the texture properties. A side effect of this approach is the possibility to render the textures on dynamic objects as well.

During an experiment these scenes are presented to an observer in fixed or random order. While the experiment is running, the movement of the PHANToM can be recorded and played back later using the force-feedback device as a robot that guides the observer's hand.

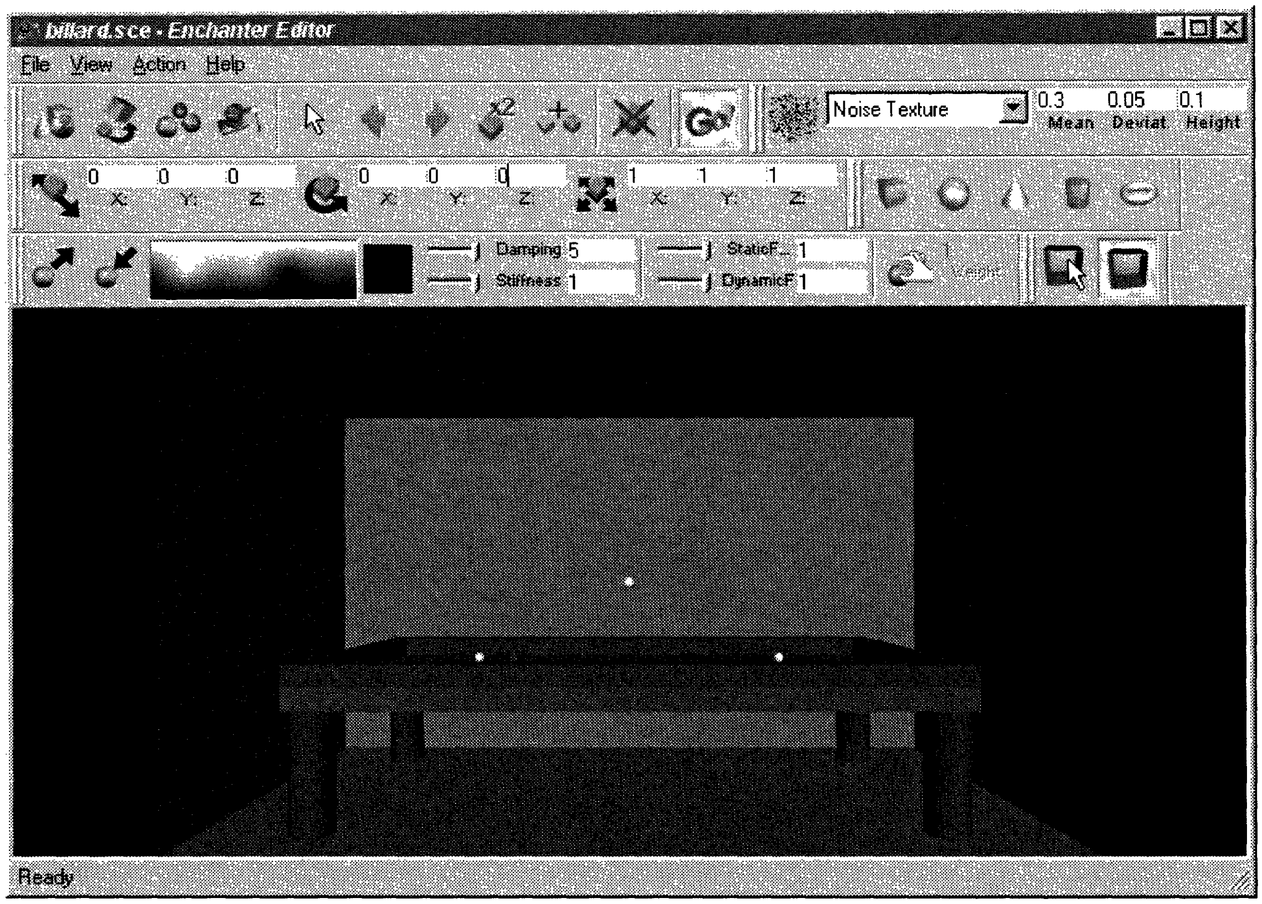

Figure 1. ENCHANTER with example of scene (not used in the experiments).

Experiment 2a. Blindfolded Sighted Observers

Four virtual geometric forms of three sizes, rendered by a PHANToM 1.5A under ENCHANTER, were presented to ten paid blindfolded sighted university students who explored the objects with a stylus. The experiment is described in more detail in Jansson (1998). The result was that the observers could very effectively identify the virtual forms, especially after some experience with the device. For the second and third replication of the stimuli 95 % of all the forms and sizes were correctly identified within an exploration time of about 10 - 20 sec (range for the means of each stimulus).

Experiment 2b. Visually Impaired Observers

Problem. The experiment just mentioned demonstrated that vision is not necessary for correct identification of 3D geometric forms. Even if a similar result can be expected to be applicable also to a comparable group of visually impaired observers (especially concerning the relations between the experimental conditions), there may be complications for these observers. On one hand, they have more training in using the haptic sense; on the other hand, they have less experience of spatial relations in the environment as these are experienced by sighted people. The absolute level of the results may be different, the former fact suggesting a better result, the letter a not as good one. Further, it would be of interest to investigate the result in a group with wider range in age and, maybe, abilities. How will such a group of visually impaired observers perform in a task similar to the one in Experiment 2a?

Virtual Geometric Forms. Four 3D forms (sphere, cube, cylinder, and cone) in five sizes (all three dimensions being 6, 8, 10, 50 and 100 mm, respectively) were rendered with a PHANToM 1.5A under ENCHANTER. In order to simplify finding the objects, each was localized in the middle of a cubical enclosure its dimensions being 20 mm for the three smaller forms and 100 and 200 mm for the 50 and 100 mm forms, respectively. To help the discrimination between object and enclosure, the object to be identified was given no static friction and the insides of the enclosure were given high such friction.

Procedure. The observers were informed about the PHANToM and the safety aspects and they were allowed to acquaint themselves with the device. The geometric forms to be used were explained and wooden models of the forms (all three dimensions being 25 mm) were demonstrated. There were no restrictions applied on how the observers should hold the stylus, but the observers usually held it similar to a pen. A head protective device common in industry was applied, as was an eye cover for observers with any remaining vision. Further, earphones were applied to mask any sound by playing white noise[1]. Before the experiment proper, the observers were allowed to try up to ten objects of different form and size under the experimental conditions without any recording.

During the experiment the observers were presented with three blocks of all the virtual objects (four objects in five sizes) one by one in random order within the block, thus in all 60 objects. The observers' task was to name the form of the objects as fast and accurately as possible, with equal emphasis on both aspects. A maximum of 60 sec was allowed for each object. The time elapsing from the start of exploration within the enclosure until the beginning of the response was recorded, as was the verbal response.

Observers. Ten visually impaired persons (three women and seven men) were paid to participate. Their age varied between 23 and 50 years with a mean of 38 years. Six of them were totally blind; of the remaining four two had some sense of light and two had some low vision within a small visual angle. One of the observers got blind when in an incubator; the others had been sighted for different numbers of years. They had been visually impaired for 6-31 years.

Results. Six of the ten observers got results similar to those of the sighted blindfolded observers in Experiment 2a. Their results are given in Fig. 2. Four of the observers had difficulties in performing the task, resulting in many mistakes and unfinished tasks.

Discussion. The result in Experiment 2b differed partly from that in Experiment 2a. Six of the visually impaired observers performed similarly to the sighted observers, but four did not. The two groups were not matched and they are too small to make detailed comparisons meaningful, but one hypothesis, based on informal observations, is that the visual impaired observers with low performance had some basic difficulties in understanding the task, finding the objects, and/or exploring them in an effective way. A follow-up study where low-performing observers are asked to return to get training in finding and exploring the virtual objects before new test sessions is in progress.

General discussion

The experiments demonstrated that the texture and 3D form of virtual objects rendered with a PHANToM device can be perceived accurately and with reasonable speed without the guidance of vision. Experiment 2b demonstrated that many visually impaired observers can perform on the same level as blindfolded sighted observers, but

[1] It can be discussed if masking sound should be used. If the practical situation of a visually impaired person using the PHANToM is considered, sounds may be looked upon as additional potentially useful information and not masked. On the other hand, if the capabilities of haptics alone is considered the sounds should be masked. There were indications in Experiment 2a, where the sounds from the PHANToM were not masked, that the sounds produced when the stylus end passed edges might have been used by the observers. We chose here to study haptics alone and applied thus a masking sound.

also that some observers with visual impairment have problems in performing the task. An experiment in progress investigates if these problems can be solved by extra training of the exploration method.

It should be noted that the haptic perception of only a few properties of 3D objects have been investigated. Many aspects remain to be studied. An important parameter for future studies is the complexity of the virtual scene. A reasonable hypothesis is that increase of the complexity of texture and 3D form would mean increased problems for haptic perception of the virtual scenes.

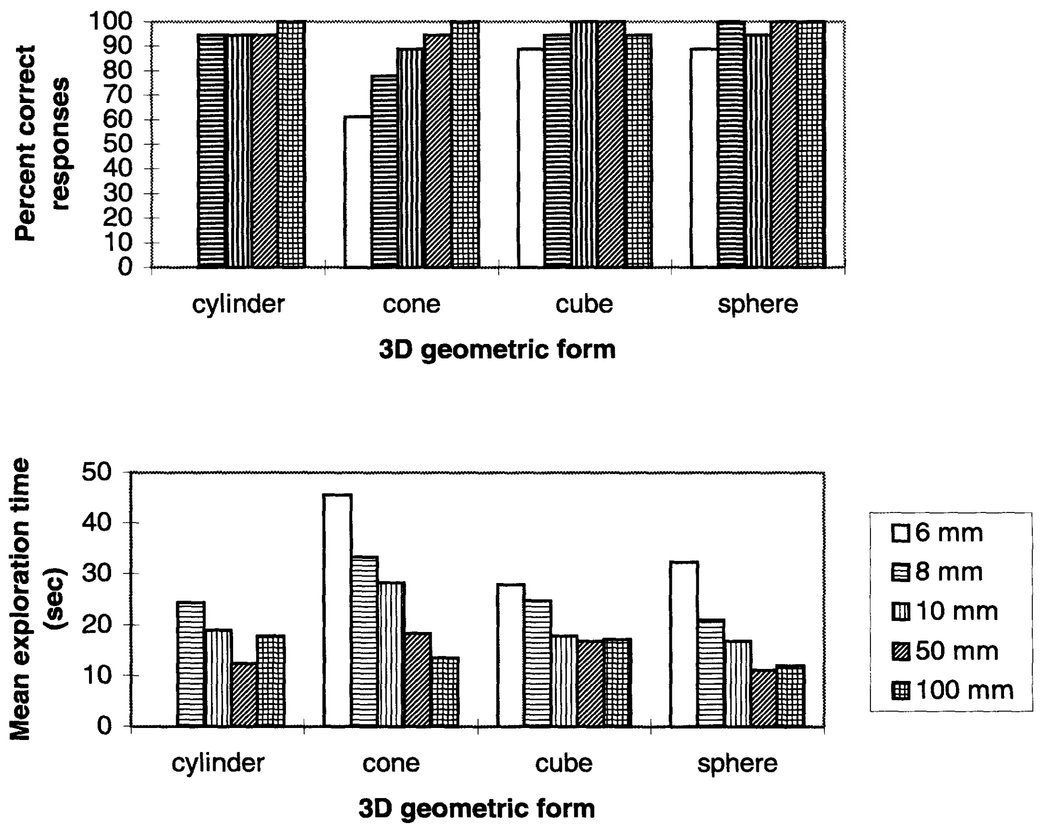

Figure 2. Means of percent correct responses (top) and of exploration times (bottom) for each of the objects for six of the ten observers. (Data for the 6 mm cylinder missing for technical reasons.)

Acknowledgments

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Psychophysical experiments in a complex virtual environment

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Abstract

We are using two PHANToM 3.0 force feedback devices in one workspace in order to perform studies of one-hand precision grip tasks or two handed pointing tasks. The visual environment is rendered by an Onyx workstation and presented in a specialized stereo head mounted display that allows eye tracking. The head position and orientation is tracked with an electromagnetic system (Fastrak). Together, these systems allow the current gaze direction in world coordinates to be computed in real time. The artificial visual and haptic environment may contain free movable objects as well as stationary parts, whereas the objects can be complex or simple. The graphical user interface allows all object properties to be changed online. In addition, we are using free programmable force effects that depend on position or velocity information. Psychophysical experiments that simulate eye-hand coordination in complex 3D scenes demonstrate results that seem to be in line with previous research in real environments. Thus, we believe that the dual-PHANToM instrument is an experimental device that is well suited for various studies of visual motor coordination, with special reference to aspects like timing and adaptation.

keywords: human experiments: psychophysics, vision, sensori-motor control; virtual reality

1 The Virtual Reality Setup

The National Institute of Health (NIH) Virtual Reality Lab integrates several devices in one co-located environment in order to simulate many aspects of human sensori-motor coordination. Devices like head mounted displays (HMD) and 3D position and orientation trackers (Fastrak, Polhemus Inc) are used to present a virtual scene for subjects, in which they can interact using a force feedback system (PHANToM, SensAble Technologies, Inc.). All devices are integrated in a flexible experimental setup, in which movable as well as stationary virtual objects and their physical properties can be controlled by the experimenter. The program controlling experiments and virtual presentations to subjects allows online control over all parameters concerning the objects and the devices. The simulation runs on a specialized Onyx Infinite Reality machine (Silicon Graphics, Inc.). The graphical rendering as well as the haptic interactions are controlled by the same computer in order to minimize the latency of the simulation.

1.1 The PHANToM 3.0

The current system is designed to have two PHANToM 3.0 force feedback devices acting in one physical and virtual workspace with a dimension of 30x40x40 cm. The two PHANToM devices face each other, mounted on epoxy blocks situated on a table (Fig. 1).

A crucial setup problem is to achieve an exact alignment of the workspaces of the two PHANToMs. Each device needs to be calibrated to the precise location in the shared three dimensional workspace. Through careful calibration of the mounting position and by using an optimal starting position (90 degree angles) for the PHANToM arms, we achieved an error below 1 mm on average between the physical point in 3D space and the virtual space of each

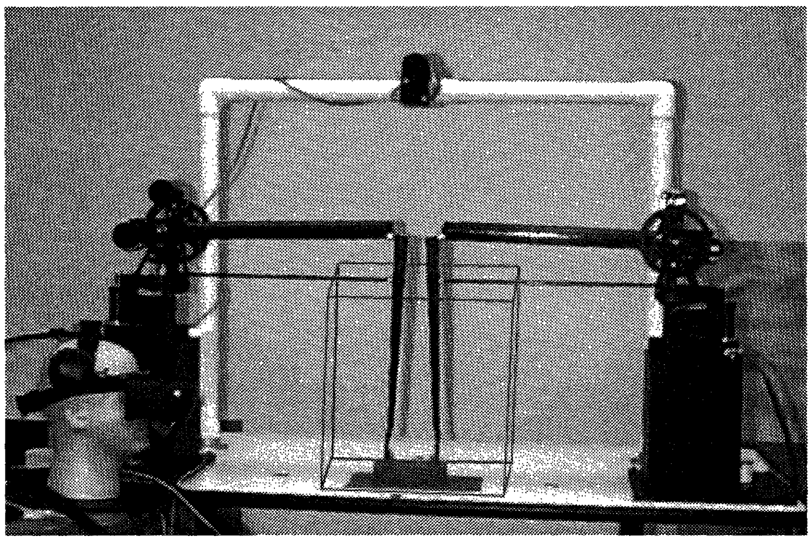

Figure 1: The VR setup with workspace (cube)

PHANToM. The average distance for the same physical point between both PHANToMs is below 1.5 mm. However, the errors increase from the calibration center towards the edges of the common workspace (see Fig. 2 for more details on the error distribution).

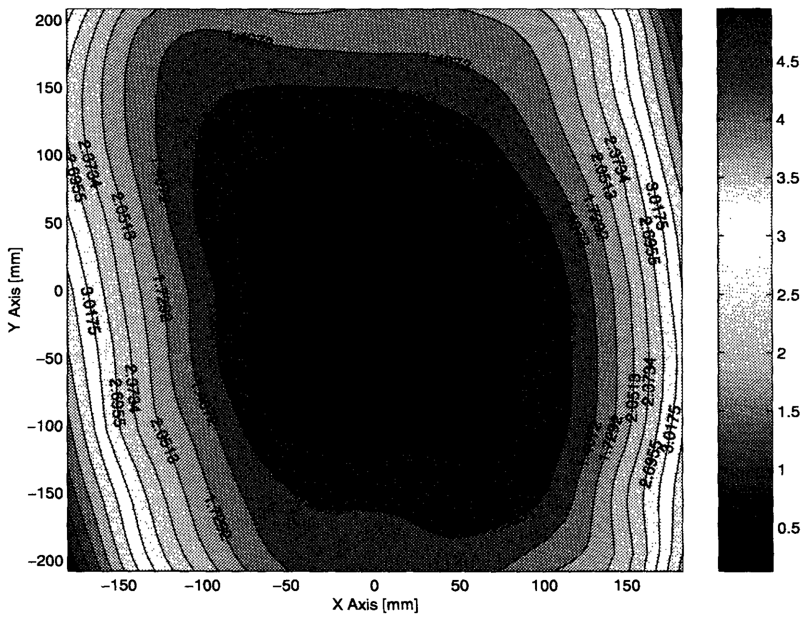

Figure 2: Contours of position mismatch in mm

1.2 Head Mounted Display with eye-tracking

The observers perspective of the scene is presented in a V8 HMD (Virtual Research Systems, Inc.) and depends on the position and orientation of the subject's head in real 3D space. This six-degrees-of-freedom tracking is realized with the Fastrak device. Low frequency magnetic fields are generated by three co-located antennas inside a transmitter and received by similar remote antennas inside a receiver. The signal is transformed by a mathematical algorithm to compute the relative distance and the orientation for the transmitter and the receiver. The appropriate view is presented to the subject inside the helmet with a delay below 30 ms. The resolution of the LCD is VGA standard (640x480 pixels for each eye) in true color and the screen is updated with a frequency of 60 Hz.

The customized HMD allows the tracking of movements of the subject's left eye. A built-in eye-camera connected to a separate computer provides information of the subject's gaze angle. Since the presented view is known in detail, the program can intersect the ray of sight with the virtual scene and calculate where the subject is looking. This information is valuable for experiments that address eye-hand coordination as well as experiments that focus on human memory (for more examples see [Jackson *et al.*, 1995], [Messier and Kalaska, 1997] and [Toni *et al.*, 1996]). The lab is in the process of developing several experiments along these lines.

2 Psychophysical experiments

The device has special characteristics that have to be considered when doing psychophysical experiments in this virtual environment. For instance, the normal tactile feedback when touching and handling an object is absent. Instead, the skin of the fingertips is in constant contact with the inside of the finger thimbles. Cutaneous receptors normally provide the central nervous system with information related to touch and slippage between the object and the finger when we grasp something. The character of the surface material in contact with the fingertips is therefore essential for the fingertip force coordination when handling real objects. We observed that the surface inside the thimbles strongly influences the force that the subjects apply, even though the force feedback gives the subject information about object contact (see below).

In a virtual environment as rich and complex as this, one can think of a variety of studies. Of particular interest are experiments that not only allow a good approximation to similar conditions in reality, but that also add control over parameters that are not easily studied or manipulated under normal conditions.

The current software was developed to design and control experiments involving many different parameters including object properties such as: mass, visual and haptic size, color and texture, transparency, surface spring, surface damping, dynamic and static surface friction, surface smoothness (necessary only for complex shapes), object elasticity during collisions etc. Additional features involve control over the field of gravity, viscous damping in the surrounding medium, position and velocity, haptic and visual rendering, collision detection and even movement restrictions to planes and axis. Moreover, the program allows control of some HMD parameters and offers a fast and flexible interface to data collection. The data is already processed by the computer and only has to be saved to a file at an adjustable sampling frequency of up to 1000 Hz. Most of the object properties and the device settings can be predefined in configuration files or controlled online via the graphical user interface. Specialized control windows offer a flexible design and setup of separate experiments in a short time.

Below we present some examples of experiments in which different tasks involving sensori-motor control in the virtual environment have been studied. These serve to illustrate the potential of the device and the program.

- **Sorting objects by weight:**
  Subjects sorted four cylinders according to their weight, which was randomized to any value between 25 and 250 g. In addition, the size of the cylinder could vary independently. The results of the classical weight-size illusion were confirmed, i.e., subjects make systematic errors in discriminating objects of similar weights, when the size is not related to the weight, by judging a bigger object as being lighter ([Woodworth and Schlosberg, 1938]). An analysis discriminating between the subject's ability to detect mass or density was used to implement a linear model that could explain the error rate.

- **Reaching through force fields:**
  Subjects performed reaching tasks from a starting point towards a final point, which could be an object as well as just a marked target/region in space. Experimental conditions like invisible fingertips, invisible targets at the onset of the movement ([Miall and Haggard, 1995]) and different instructions concerning the speed of

the movement showed results in accordance with previous findings in reaching tasks ([Jeannerod, 1984] and [Jeannerod, 1988]). When a force field was introduced during the movement somewhere between the start and end point, the subject adequately compensated for the perturbation. In one experiment the force field depended on position (see [Conditt *et al.*, 1997] for similar experiment) and in the other case it depended on the subject's fingertip velocity (see artificial perturbation in [Coello *et al.*, 1996]). In both cases the subject was able to adapt after a couple of trials.

- **Lifting cylinders with different physical properties and with a reversed field of gravity:**
  In another series of experiments the subjects performed simple lifts of an object (cylinder). The visual properties were always constant, but the haptic conditions and physical properties of the object were changed between trials. In the analysis we separated the force perpendicular to the field of gravity (grip force) and the lifting force in the direction opposite to the field of gravity (load-force). The grip and load forces are coordinated in parallel and are directly related to various object properties like weight, size, shape etc as shown in a number of studies by Johansson and colleagues (for review see [Johansson, 1997]). Subjects applied grip and load forces according to changes of the physical properties of the object and to changes of the direction of gravity. The surface in contact with the fingers in the thimbles was important for the grip force regulation. A more slippery surface like the standard metal thimble results in higher grip forces throughout the lift compared to when sandpaper was used inside the thimbles.

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