IMPLEMENTATION AND EVALUATION OF A HAPTIC PLAYBACK SYSTEM
FOR THE VIRTUAL HAPTIC BACK

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FOR THE VIRTUAL HAPTIC BACK

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This thesis presents implementation and evaluation of a haptic playback system using the PHANToM haptic interface, in the context of our Virtual Haptic Back Project at Ohio University. Playback has the potential to improve virtual palpatory diagnosis training by allowing students to follow and feel an expert’s motions in virtual reality prior to performing their own palpatory tasks.

We have two types of playback system. The first type is called ‘Combined Playback System’ and the second one is called ‘Two Mode Playback System’. In the first type we have a combined position and force playback. In the second type of playback system, in mode 1 the human is passive and experiences position playback of the expert’s tactile examination via the PHANToM with a PD position controller. In mode 2 the human traces the expert’s path actively through visual cues. Mode 2 enables the haptics model so that the trainee feels approximately what the expert did in the original task.

Both playback systems are evaluated. Our experiments show that if both playback modes of the ‘Two Mode Playback System’ are used together, trainees follow the expert’s path with lesser position error than the other group, which doesn’t do mode 1 training.

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1. Introduction

1.1 Background and Literature Review

Haptics, the science of touch, is an inescapable part of our future. It will make it possible for man to access places that are typically too dangerous or expensive to go. Haptics is been applied in virtual reality environments to increase realism. The idea is being implemented in two ways. The first scenario involves a computer model and a haptic interface. The subject is being modeled both graphically and haptically and the user can see the rendering on the computer screen while feeling it via some haptic interface.

Haptics has been applied recently to education and training, most notably in the medical field. Surgical training could be made more economical, more realistic, more accessible with the implementation of haptics. Anatomy lessons could be taught using virtual reality. Currently, cadavers are used for medical training. Cadavers are costly, limited, and unrepresentative of live human anatomy. Live tissue has a different set of properties than non-living and chemically treated tissue.

In the Stanford Visible Female project (Heinrichs, et al., 2000), a 3D stereoscopic visualization of the female pelvis has been developed from numerous slices of 2D pelvis data. Haptic feedback was enabled via the PHANToM haptic interface, allowing the user to interact with and feel the virtual model. The Interventional Cardiology Training Simulator (Shaffer et al., 1999) links technical simulation with specific medical education content. A virtual reality-based simulator prototype for the diagnosis of prostate cancer has been developed using the PHANToM haptic interface (Burdea et al., 1999). The
same research group is developing a force-feedback glove (Bouzit et al., 2002). Another tumor palpation virtual reality (VR) simulation was developed by Langrana (1997). The Immersion Corporation (www.immersion.com) has developed haptic interfaces for injection training and sinus surgery simulation. Delingette (1998) is working on realism in modeling human tissue for medical purposes. The GROPE Project (Brooks et al., 1990) has developed a 6D haptic/VR simulation of molecular docking. The SPIDAR haptic interface has been adapted to serve as "the next generation education system" (Cai et al., 1997). Basdogan et al. (2001) simulate a surgical catheter procedure using a pair of laparoscopic forceps with haptic feedback for medical training. Tendick et al. (2000) use a virtual environment including a 4-dof haptic interface for minimally-invasive surgical training. Georgetown University Medical School is developing a spine biopsy simulator for surgical training, including a PHANToM haptic interface and a physical model (Cleary et al., 1997). An example of injection simulators with haptics is presented by Dang et al. (2001).

Adams, Klowden, and Hannaford (2001) have shown a significant improvement in subject performance in a real-world Lego assembly task with VR training including force feedback. A group at the University of Ioannina in Greece is involved with virtual learning environments including a Power Glove with tactile feedback to "build a theoretical model for virtual learning environments, expanding constructivism and combining it with experiential learning" (Mikropoulos and Nikolou, 1996). A research group at the Ohio Supercomputing Center has applied haptics in virtual environments to improve tractor safety by training young rural drivers (Stredney et al., 1998); their results show haptics increases training effectiveness. Haptics has been applied to make virtual
environments accessible to blind persons (Jansson et al., 1999). Affordable haptic interfaces have been implemented to augment the teaching and learning of high school physics (Williams et al., 2001). High-end haptic devices have been applied for force reflecting robotic teleoperation, e.g. Williams et al. (1998). This literature review demonstrates the significant interest in the field of haptics and graphics for biomedical applications.

We have developed a playback system in the PHANToM haptic interface software environment wherein the motions and interaction forces of an expert may be recorded and saved for later ‘playback’ to trainees using the same virtual reality system. Other research groups have been including a playback feature in their work. In the aforementioned prostate tumor diagnosis work (Burdea et al., 1999), a PHANToM playback mode is used both to analyze a trainee’s performance and to show the trainee how an expert approaches prostate examinations. The same research group is applying general graphics playback in palpation training for detecting subsurface tumors (Dinsmore et al., 1997); a data file is written with all inputs from all I/O devices to replay the user’s actions graphically; this case does not involve the PHANToM with haptic playback. A second group is using a PHANToM playback feature in their horse ovary palpation simulator (Crossan et al., 2000), to implement a tutor/trainee model. Reachin Technologies (www.reachin.se) has developed a VR-based laparoscopic surgery trainer with haptics; this system allows recording of the simulator positions at all times so an instructor may rate the performance of students later. Weghorst et al. (1997) evaluate the Lockheed-Martin sinus simulator, developed with haptics by Immersion Corp.; that
evaluation used playback of videos from the various levels of sinus surgery simulation as part of their data.

This thesis focuses on the implementation and performance of our PHANToM playback systems, motivated by training needs in the Virtual Haptic Back (Figure 1.1: VHB Model) Project at Ohio University. Research groups using playback do not tend to give details about their playback implementations in the literature to date. In PHANToM (Figure 1.2: PHANToM™ Haptic Interface) playback for Virtual Haptic Back training, our first question was ‘How faithfully does our playback system replay positions and forces?’ Therefore, this thesis presents position and force error data in our PHANToM playback in the Virtual Haptic Back context. We also evaluate our system using a human factors study. First a brief overview of Virtual Haptic Back is presented, followed by a description of our PHANToM playback system, and then presentation and discussion of our playback system experiments and results.

Figure 1.1: VHB Model
Initially we had a playback system that had a combined, simultaneous 3D position and force playback tool for training augmentation. Since it is impossible to play back force and position on all three Cartesian axes perfectly, this method has errors.

To improve our first playback type, we developed a new playback system. In this second playback system type we have two modes. Mode 1 performs position playback of the recorded path. The human is passive in this mode. This gives only position feedback (not forces) of the expert’s path to the user. This mode is based on a Proportional Differential controller using the PHANToM joint torques to move the finger thimble back over the expert’s path. Our passive mode playback works with or without a human finger in the thimble. Of course, the finger must be in the thimble during the student training.

In mode 2 of this second playback system type the human is active. In this mode a ball traces the expert’s path. The user has to follow the ball in all three dimensions. If the user is able to follow the path closely in all three Cartesian coordinates, he would feel
approximately what the expert had felt. The user will not, however, feel exactly the same as expert, unless she behaved exactly the same as the expert, which is impossible. However, our training philosophy is that, if the student can feel during playback close to what the expert felt during interacting with our VHB model, we believe this may have training benefits.

1.2 Virtual Haptic Back Motivation and Overview

The VHB project is an interdisciplinary collaboration between two Ohio University colleges: Engineering and Osteopathic Medicine. Its purpose is to develop a series of computer-based, haptic simulations of the human body to assist students in the learning of palpatory techniques. The purpose of this thesis is to develop a haptic playback system. From the very beginnings of medicine, palpation (diagnosis through touch) has been an important part of the diagnostic process, for such things as organomegaly, the cardiac impulse, thoracic crepitus and fremitus, presence of masses (tumors) or herniations, and the presence of tenderness and edema. Palpation has been an additionally significant part of Osteopathic medical practice, because of its emphasis on somatic dysfunction and viscerosomatic reflexes. Palpation is an effective, sensitive, and economical way to diagnose many musculoskeletal (somatic) dysfunctions, including those that arise from visceral abnormalities via viscerosomatic reflexes. Unfortunately, the diagnosis of dysfunction by means of palpation is difficult to learn for three reasons: Palpation requires a highly trained sense of touch; medical students generally practice on each other, thus the subjects are often young and healthy; palpation on a human subject may change conditions, hence ensuing students may not be presented the same case to
feel. Virtual reality with haptic feedback shows promise for overcoming these obstacles in palpatory training. Each of these difficulties can be addressed by the Virtual Haptic Back simulator. Haptics provides the opportunity for practice to develop the sense of touch on simulated somatic dysfunction of graded intensity, presented in a reproducible way. Our simulator also provides a means for an instructor to keep track of and rate the progress of each trainee.

1.3 Playback for Training Augmentation

We believe that our PHANToM playback capabilities could have a significant impact on improving the teaching and learning effectiveness in palpatory training with the Virtual Haptic Back. As mentioned earlier we have developed two types of playback systems for training augmentation. (Refer to Appendix A for manual on how to use the playback system). We plan to use this position and force playback system in at least two ways for palpatory training. First, in attempt to improve learning, the motions of an expert physician diagnosing somatic dysfunction with VHB can be recorded and played back using both the modes and the students can practise and appreciate how an expert approaches certain palpatory problems. Second, a physician or other instructor can evaluate their students’ progress by playing back individual tests with the Virtual Haptic Back. This would provide objective data regarding the trainee’s performance, including documentation of any improvement as the training progress. This will add a quantitative component to the art of palpatory diagnosis, which has not been available prior to the VHB.
1.4 Thesis Objectives

The primary objective of this thesis is to implement and evaluate a haptic playback system for the Virtual Haptic Back. Evaluation of the playback system will be done using system evaluation and experiments with the human subjects. Training effectiveness of playback system using human subjects will be evaluated. Statistical and graphical methods will be used to evaluate the performance of the playback system.

The secondary objective of this thesis is to test if playback helps students become familiar and comfortable with the VHB.
2. Virtual Haptic Back Concept

The Virtual Haptic Back will add a component of science into the learning of the art of palpatory diagnosis. The main goals of this project are to:

1. Provide a novel tool for palpatory diagnosis training; and
2. Improve the state-of-the-art in haptics and graphics applied to virtual anatomy.
3. Investigate the effectiveness of haptics in virtual environments. (Williams et al., 2003)

2.1 VHB Product

The Virtual Haptic Back is under development to simulate the palpatory feel of the normal and the dysfunctional human back. A high-fidelity graphical model of the human back (Figure 1.1) is coupled with a haptic interface (Figure 1. 2) to allow user interaction. The purpose of this tool is to augment the teaching and learning of palpatory diagnosis and related skills in Osteopathic Medicine, Physical Therapy, Massage Therapy, and related fields.

We now present the evolution of the VHB model. The back of a volunteer subject (adult male of average size) was measured using a Metrecom Skeletal Analysis System (SAS) made by Faro Technologies Inc (Figure 2. 1). An offline graphical representation of the smoothed data from this original model is shown in Figure 2. 2.

In the initial real-time interactive model version, v0, (shown in Figure 2. 3) the feel consists of linear springs of varying spring stiffnesses, normal to the surface of each graphical polygon. As shown in Figure 2. 4, a more complex haptic model was then developed wherein a cylinder with simulated ribs is encased in a sphere of fleshy material. The idea behind this model is to allow the user to feel different layers of haptic
feedback (i.e. palpate through the fleshy material to feel the ribs beneath the surface).

Figure 2. 5 shows the first interactive virtual haptic back model, v1, that includes this layered feature, plus a model of the human spine.

Figure 2. 1: SAS 1

Figure 2. 2: Smoothed Back Data
Figure 2.3: Initial Back Model, v0

Figure 2.4: Layered Haptic Model
The VHB, v3, is shown in Figure 2.7. This model, an extension of v2, has two new features. First, movable haptic ribs have been added. Second, for the first time, two PHANTom haptic interfaces are implemented for dual-handed palpation (L and R cursors in Figure 2.7; the two PHANToMs are pictured in Figure 2.12). The circles located laterally represent the acromion process above and the posterior superior iliac spine below.
The VHB, version 4, is shown in Figure 2.8. This model, an extension of v3 with two PHANToMs, has two new features. First, the nominal graphical scaling is 1:1, including the spacing of the palpator’s fingers. The PHANToMs must be calibrated in the provided caddies for best results. The graphics can then be scaled in or out, but the haptics scaling does not change. This is equivalent to the palpator moving their head closer to or further from the virtual back image. Second, a realistic human vertebra was digitized in 3D using the Picza pin-contact digitizer (Figure 2.9). The same vertebra is used for all. The vertebra model is rough, to avoid an excessive number of graphical polygons which slows down the system. The haptics model for each vertebra has not changed, i.e. it is still composed of spheres as the DOs suggested.
Figure 2. 8: VHB, v4

For more information, and future updates, please visit the project website:

http://www.ent.ohiou.edu/~bobw/html/VHB.html

Figure 2. 9: Picza 3D Digitizer

For playback implementation and evaluation VHB, version 2, was used.
2.2 Hardware and Software

This section describes the hardware and software details of the VHB project.

2.2.1 Hardware

The Virtual Haptic Back simulation runs on a PC NT workstation. The PHANToM haptic interface (Figure 1. 2) by SensAble Technologies, Inc. uses position information input by the user to determine what forces to relay back to the user via its three motors. A flow diagram for the PHANToM is pictured in Figure 2. 10. The human finger moves the PHANToM to desired X, Y, Z Cartesian locations (sensed internally via joint encoders \( \theta_1, \theta_2, \theta_3 \)); this Cartesian input is sent to a virtual computer model. The haptic/graphical software determines what Cartesian force vector \( F_X, F_Y, F_Z \) the human should feel and the PHANToM generates this force at the human finger (accomplished internally via joint torques \( \tau_1, \tau_2, \tau_3 \)).

![PHANToM Flow Diagram](image)

Figure 2. 10: PHANToM Flow Diagram

The PHANToM 1.0 shown in Figure 1. 2 has a nominal resolution of 0.03 mm, a workspace of 13x18x25 cm, and a maximum exertable force of 8.5 N. Our PHANToM only reads positions and exerts translational forces; a passive gimbal connects the user’s finger to the tip of the PHANToM.

The VHB simulation runs on a 900 MHZ, dual processor PC NT workstation, with a Matrox Millennium 6400, 32 MB graphics card.
The Virtual Haptic Back is under development at Ohio University to augment the palpatory training of Osteopathic Medical Students and Physical therapy and Massage Therapy students (Holland et al., 2002). This project has implemented a combined graphical and haptic model of a live human back on a PC, using the PHANToM interface for haptic feedback. The target applications are the diagnoses of both somatic dysfunction and movement dysfunction.

### 2.2.2 Software

SensAble Technologies Incorporated provides a General Haptics Open Software Toolkit (GHOST® SDK). It is a C++ object oriented toolkit that represents the haptic environment as a hierarchical collection of geometric objects and spatial effects. The Ghost® SDK uses OpenGL and 3D graphics. The 1000 Hz servo loop perform the following functions

1. Updates the PHANToM node position in the scene.
2. Updates the dynamic state of all dynamic objects.
3. Detects collisions in the scene.
4. Sends the resultant force back to the PHANToM.

(Refer to Appendix B for more details on programming for the Playback systems)

### 2.3 Haptics Model

The haptics feedback in the Virtual Haptic Back is the result of a combination of different models. The vertebra and bony landmarks were created with SensAble Technologies GHOST software. Their haptics are modeled by a stiff spring-damper system. The motors in the PHANToM limit how solid these objects will feel. The spinous ligament is created as a mesh object, again using the GHOST software. The stiffness of
the mesh is set slightly lower than that of the vertebra. The feel of the mesh is also modeled by a spring-damper system. The skin is made up of two parts. The first is a mesh similar to the spinous ligament. Once a certain force threshold is exceeded, the user will push through this mesh into a second force region. This part of the skin uses a surface model. The feel of the skin in this region is determined by a linear function of the distance from the surface of the skin to the position of the user below the skin surface. The model is layered because the vertebrae, spinous ligament and bony landmarks are located within the skin force field. As these objects are being touched, the skin force is pushing the user away from them.

The values for spring stiffnesses for the skin and bone models, plus the rotational stiffnesses for the vertebrae were not measured from a live human subject. Rather, they were set by the development team according to subjective feel. We have been updating these values based on expert DO feedback for increased realism.

2.4 Features

The Virtual Haptic Back is being developed as a device for use in teaching medical palpatory skills. The operator feels resistance as the finger touches the simulated skin. As the finger is pressed into the skin, the vertebral spines or transverse processes can be felt as additional resistance sensed by the palpating finger. An image of the back being palpated appears on a computer screen along with a cursor that specifies location of the palpating finger. As the finger compresses the skin, the skin can be seen on the screen to dimple. The graphics can be set to reveal the underlying bone or not, so that the palpation can be done with or without the aid of seeing the underlying vertebrae on the screen. (The real world does not allow this choice!) Individual vertebrae can be rotated
as the operator presses on a transverse process. The resistance to rotation can be varied for each vertebra independently so as to simulate restricted vertebral motion. The initial position of each vertebra can also be set independently, via menu in order to simulate vertebrae out of position (Figure 2.11). In these ways the operator can palpate vertebral spinous processes C6 through L1. The interspinous ligaments joining the spinous processes are palpated as objects with less intrinsic stiffness (more give) than the spinous processes. Transverse processes can also be palpated lateral to the spinous processes and deeper. These features allow instructors to program various somatic dysfunctions, using pull-down menus. Students can then be asked to detect these abnormalities by palpation.

The system is still under development and will be expanded in the future to include different axes of rotation for the spinous processes (currently these rotate only about the axis of the spine), soft tissue changes, such as muscles in spasm and regions of local edema, plus two handed palpation via the new PHANToMs pictured in Figure 2.12.

Figure 2.11: Vertebra Rotation
Sound feedback is employed in the simulation to provide immediate feedback to the trainee during palpatory diagnosis practice sessions. When the trainee has identified the spinous process that is out of place, for instance, pressing a foot switch will provide aural feedback as to if the identified one is correct.
3. Haptic Playback Systems

This chapter describes our haptic playback systems. Initially we developed the Combined Playback System. Since it is impossible to play back force and position on all three Cartesian axes perfectly, this method has errors. So we developed a new Two Mode Playback System.

3.1 Combined Playback System

A haptic playback system was developed wherein experts’ position and force interactions with a haptic model may be saved and played back simultaneously to the PHANToM later. Again, it is not possible to play back positions and forces independently without errors. In our initial training application we accepted this error and performed simultaneous playback simultaneously force and position. This section discusses position and force playback separately, but it is important to remember that our implementation had combined position/force playback.

To achieve playback, two data files were created during the recording mode. One file records the $XYZ$ positions of the PHANToM and the other records its $F_X$, $F_Y$, and $F_Z$ commanded forces. In the establishment of the initial path of expert the position input comes from the user’s hand motions, read via the PHANToM encoders. Since our PHANToM does not have force or torque sensors, the recorded force data are taken to be the commanded forces in the haptic system. The position and force aspects of our combined playback capability are now described.
3.1.1 Position Playback

For recording the user’s path, points are sampled at a rate of 1000 Hz and saved in a file. These points are read and the PHANToM playback driving force $F$ is calculated using (eqn 1). This driving force moves the tip of the PHANToM back through the previously-recorded positions for playback. We use a simple proportional controller with gain $k$; a PD controller is used in the two mode playback system.

$$F = k \left( \|v\| - r \right) \left( \frac{1}{\|v\|} \right) v$$

In (1), $k$ is the virtual spring constant; $v$ is the vector distance between the current PHANToM position and the next playback point to move to (the center of an attractive spherical force field, see Figure 3.1); $\|v\|$ represents the Euclidean norm of vector $v$; $r$ is the radius of the spherical region from the center of the attractive force field (where there is zero attractive force).

Equation (1) looks complicated, but it is simply a spherical version of Hooke’s law $F = k \Delta x$. The virtual spring force is zero on the surface (and inside) of the sphere of radius $r$; the attractive force $F$ for position playback increases linearly with the radial distance from $r$. The attractive force $F$ operates radially, normal to the sphere surface in all directions.

The center of the spherical attractive force field is initially located at the PHANToM tip so the PHANToM is within the zero force region. The force field is then shifted to next recorded position. As this is done the PHANToM is moved out of the zero force region, attracted by the next force field: the driving force (1), proportional to the distance $\|v\| - r$, acts on the PHANToM and attracts it to the next zero force region. The
PHANToM has play in this spherical no-force region, so \( r \) should be small for small position error. The force field is then shifted to the next recorded position and this loop repeats at the update rate 1000 Hz. In this manner the PHANToM repeats the recorded path. \( v \) is a variable vector which changes as the PHANToM tip approaches the next position.

\[ F \propto v-r \]

\[ F = 0 \]

![Diagram showing spherical attractive force](image)

**Figure 3.1: Spherical Attractive Force**

### 3.1.2 Force Playback

Simultaneously with the position playback described above, we have implemented force playback to approximate the feel of the expert’s palpations in addition to approximating the positions. Since it is impossible to exactly command position and force independently, there is some error. The idea behind this was that for tactile training, a combination of force and position playback will be more effective, even with small errors, than choosing only force OR position playback.
There are two possible ways to implement force playback in conjunction with the above position playback. At the outset of our work we did not know which was preferable so we tested both (see Section 5).

The first force playback possibility is to record the commanded forces during the expert’s session and then command the same forces upon playback. These commanded forces are calculated from our Virtual Haptic Back Model and are dependent on the expert’s positions over time. During playback, these recorded forces are sent back to the PHANToM. A student using the playback feature will not feel the exact same forces as the expert since there is also a driving force $F$ superposed from the position playback of (1). In this first force playback case, the haptics model is turned off during playback because the forces we wish the student to feel are already recorded.

The second force playback possibility does not use the recorded forces as in the first case. Instead, while the student is experiencing the expert’s position playback the haptics model is enabled, automatically generating in real-time the appropriate forces depending on the position displacements. Of course, the same haptics model is used for the expert’s session and the student’s playback. There will be errors in the forces, again due to the simultaneous position playback driving force $F$.

In the results plots of Section 4.1, these two force playback options are called ‘With recorded force’ and ‘Without recorded force’, respectively.

### 3.2 Two Mode Playback System

Since it is impossible to develop a haptic playback system, which can exactly reproduce experts’ position and force interactions with a haptic model, we have
developed a second playback system called the *Two-Mode Playback System*. In this second playback system there are two modes. The first mode i.e., the passive mode, replays position using the PHANToM and a PD controller and helps the user experience the expert’s path. In this mode the human is passive. The second mode i.e., the active mode, demands an active participation and helps the student to feel the tactile examination that the expert has done through its various visual cues. It is true that it is impossible to exactly follow a prerecorded path but in our training application we would rather accept this error, since we believe that our PHANToM playback capabilities could have a significant impact on improving the teaching and learning effectiveness in palpatory training with the Virtual Haptic Back. In the future, during the course of our human subject evaluations, we will evaluate training effectiveness of our playback system by comparing two similar groups of trainees, one with and other without playback training. This section describes the implementation of the two modes of the playback system.

To achieve playback, two data files are created during the recording mode. One file records the *XYZ* positions of the PHANToM and the other records its *F*\textsubscript{X}, *F*\textsubscript{Y}, and *F*\textsubscript{Z} commanded forces. In the original simulation the position input comes from the user’s hand motions, read via the PHANToM encoders. Since our PHANToM does not have force or torque sensors, the recorded force data are taken to be the commanded forces in the haptic system.

The two modes of our two-mode playback system are now described.
3.2.1 Mode 1 (Passive)

In this mode the user is passive. The user puts her/his finger in the thimble and the PHANToM traces the expert’s path. We have implemented a PD controller for this mode 1 passive position playback. No haptics mode is allowed in playback mode 1 since the PHANToM motors are already devoted to the PD position controller.

The expert’s $XYZ$ positions are read and the PHANToM playback driving attractive force field $F$ to playback these positions is calculated using the PD controller of (1):

$$F = K_p e + K_D \frac{\Delta e}{\Delta t}$$

where:

$$\Delta e = \frac{(\Delta X_{pb} - \Delta X_{ex})}{\Delta t}$$

The subscript $pb$ indicates playback position, while $ex$ represents the expert’s position. The gain $K_P$ is a virtual spring to pull the PHANToM thimble to the desired expert’s position at all times, and the gain $K_D$ is a virtual damper for better stability. Note that (2) is a three-dimensional vector equation, but we found that identical scalar gains were sufficient for the $X$, $Y$, and $Z$ directions. $X$ represents position vectors $\{x \ y \ z\}^T$ and $F$ represents Cartesian force vectors $\{F_x \ F_y \ F_z\}^T$.

We determined the gain values $K_P$ and $K_D$ by trial-and-error. $K_D$ was initially set to zero and $K_P$ was increased until the passive playback performed well. $K_D$ was then increased from zero until further increase introduced oscillation. The gains were found to be $K_P = 0.38 \ N/mm$ and $K_D = 0.15 \ N-sec/mm$. 
The force field and the PHANToM tip are initially located at the initial expert path point. The force field center is then shifted to the next recorded position. As this is done a driving force (1) acts on the PHANToM. The force field is shifted to next recorded position and this loop repeats at a rate of 1000 Hz. In this manner PHANToM plays back the recorded path. $e$ and $\Delta e$ are variable vectors which change as the PHANToM tip approaches the next point. For recording the trainee’s path for later comparison with the expert’s path, points are again sampled at a rate of 1000 Hz. Again, no haptic feedback is allowed in mode 1 since the PHANToM motors are occupied only with PD position control.

3.2.2 Mode 2 (active)

In the second playback mode the trainee must actively provide the playback position (she/he is not passive as in mode 1; there is no PD position controller). In this mode, a target ball (green) traces the recorded expert’s path and the user has to follow it in all three dimensions (see Figure 3.2, where the error is exaggerated for clarity). The $XYZ$ coordinates are read from the recorded position file and the target ball traces the points. In Figure 3.2, $X$ is horizontal to the right, $Y$ is vertical up, and $Z$ is normal to the page, out. To help the trainee play back the $Z$ component (depth into back), a rectangular bar is used, which increases in length if the position error in the $Z$ direction is increases.

Mode 2 helps the trainee to feel the approximate tactile examination that the expert did since the haptics model is enabled while the trainee is providing the position playback. If the user is able to match the target ball in the $XYZ$ directions over all motion, then she/he would feel approximately what the expert had felt. The feel cannot be exact
due to small position errors upon active playback, plus differences in the expert’s and
trainees’ approach to the Virtual Haptic Back. However, we believe the haptic feel will
be close and thus may have the potential to significantly improve our virtual palpatory
training.

The user positions and forces are recorded during active mode playback trials.
Chapter 4 presents an experiment to evaluate our active mode playback method, with and
without prior playback passive mode training.

![Figure 3.2: Active Mode 2 with Error Bar 1](image)
4. Playback Experiments

This chapter describes various experiments conducted and also explains the results for the combined and the two mode playback system.

4.1 Combined Playback System

This section presents the combined position/force playback experiments and the results obtained for four different cases: with and without the human finger in the PHANTom thimble, using the two forced playback options described above. Our main objective was to determine the performance of our playback system. This is why we consider the case in which the human has no interaction with the system, while the PHANTom is tracing the recorded path, since the human finger can unintentionally affect the results. In this case no one can feel the interaction forces, of course, but the force playback mode (one of the two options) is enabled for a fair comparison with the human finger cases. Since ultimately it is the human who is going to use the system for palpatory training we then tested the system also with human finger in the thimble. In this case the human is trained to be passive and impede the PHANTom as little as possible. The former case will set an error baseline, i.e. the minimum possible system error. It is true that the human finger can add damping and thus better stability for the system; however, our results will show that the human finger also unintentionally causes more erratic behavior.

For testing purposes, we have four variations of our combined playback system.

1. With Haptics model on, no recoded forces are sent, without finger in thimble.

2. With Haptics model on, no recoded forces are sent, with finger in thimble.
3. With Haptics model off, recoded forces are sent, without finger in thimble.

4. With Haptics model off, recoded forces are sent, with finger in thimble.

For the combined position/force playback experiments an arbitrary path of approximately 42 seconds was used (it consisted of 41,957 path points, which corresponds to 41.957 seconds at the 1000 Hz update rate). The path was made to interact with the virtual human skin, spine, interspinous ligaments, and the scapula. In order to compare the effectiveness of the system under different position playback values of \( k \) and \( r \), plus the two different force playback options, the same path is used for all cases.

**4.1.1 Position Errors**

The differences between the recorded position from the expert and those obtained during playback are calculated in the \( X, Y, Z \) directions. In this thesis, a mean square error (MSE) measure is used for position errors:

\[
MSE = \frac{\sum_{i=1}^{n} \sqrt{(X_{iR} - X_{iP})^2 + (Y_{iR} - Y_{iP})^2 + (Z_{iR} - Z_{iP})^2}}{n}
\]  

(3)

\( X_{iR} \) is the recorded and \( X_{iP} \) the played-back \( X \) component of position at the \( i^{th} \) point; the \( Y \) and \( Z \) terms are defined in a similar manner. This error measure is calculated for the entire set of points, summed as shown, and divided by the total number of sampled points \( n \) to obtain the mean square error. We also calculate the standard deviation to give a measure of the spread of position errors over the playback path.

While playback is performed, the positions of the PHANToM are compared with the recorded positions and the mean square error is calculated. These are repeated for different values of \( k \) and \( r \), with and without the human finger, and with the two force playback options.
$k$ is the virtual spring constant for position playback; the higher the value of $k$, the stronger the position playback force that is sent to the PHANTom. Higher values of $k$ reduce the error, but also can introduce an unwanted buzzing effect. The attractive force is developed in a concentric sphere with no force at the center; $r$ is the radius of the spherical region where there is no attractive force as described previously (see Figure 3.1). So a larger value of $r$ would introduce more play for the PHANTom and the position error would increase. But the value of $r$ cannot be reduced indefinitely (to zero), as this can also introduce a buzzing effect. The buzzing, a haptic instability, is the result of the force field pushing the PHANTom out of the force field and the user pushing it back in. The buzzing effect also occurs when the human finger is not present due to the competing playback driving force and the force feedback. When the human finger is present, the buzzing effect occurs for smaller $k$ and larger $r$ than for the no finger case (we wish to set $r$ to zero and $k$ as large as possible for low error, but the buzzing effect prevents this).

For different values of $k$ and $r$ the position $MSE$ is calculated and the results are plotted (see Figures 4.1 – 4.4). The results are discussed below and are as predicted: smaller $r$ and larger $k$ tend to yield lower position errors. For the results of Figure 4.1 and Figure 4.2, a nominal constant value of $k = 0.38 \text{ N/mm}$ was used, and $r$ was varied by steps of $0.10 \text{ mm}$. In the results of Figures 4.3 and 4.4, a nominal constant value of $r = 0.06 \text{ mm}$ was used, and $k$ was varied by steps of $0.02 \text{ N/mm}$. In all plots of Figures 4.1-4.4, error bars are included (for the case ‘With recorded force’, shown in solid blue), showing the ± standard deviations to scale with the $MSE$ at all points. Error bars are not included for the cases ‘Without recorded force’ (but with haptics model on, shown in dashed green) simply because the plots are too cluttered; the $MSE$s can be easily
compared in the plots, and we will discuss the error bars for these cases below. For black & white printouts of this thesis, the solid blue curve is always above the dashed green curve in Figures 4.4-4.5.

In Figure 4.1 and Figure 4.2 we see that as the radius $r$ decreases (as the spherical volume where there is no attractive force decreases), the position error decreases. Conversely, in Figure 4.3 and Figure 4.4 we see that the position error decreases as the spring stiffness $k$ increases. In Figure 4.1 and Figure 4.2, the inclusion of recorded force in the playback (without the haptics model enabled) and not including the recorded force in playback (but enabling the haptics model) makes little difference in the error; the latter case yields slightly lower $MSE$. For Figure 4.3 and Figure 4.4, the difference is more significant, with inclusion of the recorded force causing greater position error.

![Figure 4.1: Position $MSE$ vs. $r$, With Finger](image-url)
Figure 4.2: Position $MSE$ vs. $r$, Without Finger

Figure 4.3: Position $MSE$ vs. $k$, With Finger
Comparing Figure 4.1 and Figure 4.2, there is almost no difference in the error when the human finger is included or not included. Comparing Figure 4.3 and Figure 4.4, the cases with human finger cause higher position errors, with the exception of higher $k$ values, which yielded roughly the same errors with or without the finger. This result may not be expected by readers since the human finger is known to increase damping and thus potentially decrease errors. However, despite trying to remain passive, the human finger may tend to fight the position playback controller, causing a user-induced oscillation and leading to higher errors.

The error bars showing the standard deviation with the MSE (for the ‘With recorded force’ cases) are fairly tight and uniform for Figure 4.1 and Figure 4.2, where $r$ varies. However, the error bars in Figure 4.3 and Figure 4.4 where $k$ varies are more erratic and much larger. As $k$ increases, this problem decreases. For the cases ‘Without recorded force’, the error bars are not shown, to avoid clutter. In Figure 4.1 and Figure 4.
In Figure 4.3 and Figure 4.4, the unshown error bars are less in magnitude and less erratic than the ones shown.

One might expect the ‘With recorded force’ and ‘Without recorded force’ cases in Figure 4.2 and Figure 4.4 to be the same since no human finger is involved. However, the differences seen in position errors are due to the different force playback options.

4.1.2 Force Errors

Since our PHANToM does not have force or torque sensors, we cannot read an actual force to compare with the commanded force to determine an error. One would expect the force error to be always zero, the commanded force less itself. However, remember there is an additional force, the position playback driving force $F$. During playback commanded forces are compared with the total forces (commanded forces plus forces required for position playback). We again use a mean square error ($MSE$) measure for force errors, analogous to (2). We again calculate the force error standard deviation to give a measure of the spread of force errors over the playback path.

The force errors plotted in Figures 4.5-4.8 are for the same conditions as those of the position errors of Figure 4.1 to Figure 4.4; they are for the same exact experiments since we combine position and force playback. The force errors obtained are small, on the order of 0.3 – 0.4 $N$ for all cases (Figure 4.5 – 4.8). For the results of Figure 4.5 and 4.8, a nominal constant value of $k = 0.38 N/mm$ was used, while in the results of Figure 4.6 and Figure 4.7, a nominal constant value of $r = 0.06 mm$ was used. For black & white printouts of this thesis, the solid blue curves are intertwined with the dashed green curves.
of Figure 4.5 – 4.8; the blue curve is the one with the error bars. The meanings of these colors and line types are identical to those in Figure Figure 4.1 to Figure Figure 4.4.

Figure 4.5: Force $MSE$ vs. $r$, With Finger

Figure 4.6: Force $MSE$ vs. $r$, Without Finger
Unlike the previous four plots for position error, the force error plots above indicate that there is little effect of $r$ or $k$ on the force error; all curves are relatively flat. The reason for this behavior is that the average forces involved during recording of the expert’s path and during the playback are relatively small of the order of 0.3 N. Also, the
two force playback options do not affect the error much either. Generally, when the human finger is involved, the force errors are higher and more erratic than when the human finger is absent, for the same reason as explained earlier for the position playback.

In Figure 4.5 to Figure 4.8, the error bars shown are very consistent, indicating a nearly constant standard deviation over all cases. In all cases, the unshown error bars are nearly identical to the shown error bars.

### 4.1.3 Example Path Deviations

The position mean square errors and standard deviations help in showing how faithful the overall position playback is. But it does not tell us anything about the error around the path. For instance, is the error larger at the beginning or at the end or at places where the PHANToM interacts with the objects in the scene? In Figure 4.9, two curves were drawn, the red one representing the recorded positions and the green one showing the path traced by the PHANToM upon playback. It was observed that the two lines were close throughout the entire motion, so the position error is fairly evenly spread. For black & white printouts of this thesis, the solid red path is darker than the green path in Figure 4.9.

The data corresponding to Figure 25 are: position $MSE = 0.95 \ mm$, position standard deviation $= 0.26 \ mm$, $k = 0.38 \ N/mm$, and $r = 0.06 \ mm$, without the human finger in the PHANToM thimble and without force playback (but with the haptics model on). This case is one example from our many experiments, with 41,957 sampled points. All experiments behaved similarly to Figure 18 in terms of even spread of position error.
4.1.4 Discussion

The experimental results for the combined position/force playback method behaved as predicted. The position error increased with increasing $r$ and decreased with increasing $k$. However, the experiments were necessary to set good numerical values for $r$ and $k$ for our training simulation. The position playback accuracy is reasonable, observed through numerical, graphical, and subjective means. The force errors remained relatively constant, with little or no dependence on $r$ and $k$. The previous two subsections discussed the effects of the human finger and two force playback options.
As discussed previously, it is impossible to exactly reproduce positions and forces independently. The position playback driving force superposes and interferes with the desired haptic forces. Therefore, using our approach, upon playback the student will not necessarily feel the same forces that the expert first experienced. Due to human differences between the expert and playback student, it would be impossible anyway to exactly reproduce the expert interaction forces.

Based on our experimental data and subjective experience with our PHANToM force and position playback system, we are confident that we may use our playback system for palpatory training in the future with small position and force errors from the PHANToM hardware and software system, using our combined position/force playback approach. A more critical error source will be the student, who must be instructed carefully in the use of the playback feature.

For the Virtual Haptic Back simulation at Ohio University (a complex haptic model), we will use the playback parameters $r = 0.06 \text{ mm}$ and $k = 0.38 \text{ N/mm}$. These were chosen from the presented data and implementation trials in our system. They were chosen as a tradeoff between small position errors and the need to avoid the unacceptable PHANToM buzzing effect.

With the haptics model turned on in playback (without recorded forces), the unwanted buzzing occurs for smaller $k$ and bigger $r$ than with the haptics model off (with recorded forces played back). Therefore, along with the above $r$ and $k$ ranges, in training we will use the force playback option where the haptics model is turned off (with recorded forces on) for our combined haptic playback.
For general complex haptic models with our combined position/force PHANToM playback implementation, from our data and experience we believe that the parameters should be kept in the ranges $0.05 \leq r \leq 0.10$ mm and $0.3 \leq k \leq 0.4$ N/mm. However, different models may change these values. Also, using a PD controller in place of our P controller for position playback may change these values; therefore, more work is required before making specific general recommendations.

The goal of playback in our Virtual Haptic Back project is to improve student training, technique, and retention, by following approximately the recorded positions and forces (for various scenarios) of an expert in tactile palpation of the simulated live human back. The position will be in error because of the zero force radius $r$ and simultaneous force feedback; the force feel will be in error due to superposition of the position playback driving force $F$ and differences between the active expert and passive student. However, the playback mode is only a precursor to the student using the simulation on their own, where the playback errors are not present. As long as the students are carefully instructed as to proper use of the playback feature and told to expect differences in feel when they use the system on their own without playback, we believe the methods of this playback system will be beneficial.

### 4.2 Two Mode Playback System Experiments

This section presents the playback experiments and the results obtained for the two mode playback system. Two different groups participated, with ten subjects each. One group was trained with playback mode 1 (passive) before being tested on the playback mode 2 (active); the other group was not given any training prior to being tested
on mode 2. The primary goal of this experiment was to test whether the group that is trained with mode 1 performs better (i.e. smaller position error) than the group with no mode 1 training, when both groups are tested with active playback mode 2.

For using this playback system experiments an arbitrary path of approximately 75 seconds was used (it was 75,452 path points, or 75.452 seconds at the 1000 Hz update rate). The path was made to interact with the virtual human skin, spine, interspinous ligaments, and the scapula.

While playback is performed in mode 2, i.e. the user is actively trying to follow the expert’s path through visual cues, the positions of the PHANToM are compared with the recorded positions and the mean square error, analogous to (2), is calculated. Each subject was asked to follow the same expert’s path seven times.

4.2.1 Experiment Description
The research subjects were divided into two groups of 10 subjects each. One group of students did mode 1 (passive) practice and mode 2 (active) with data collection, alternately, for seven trials. The other group did the mode 2 (active) with data collection only, for seven trials.

In Figure 4. 10 the average mean square error (MSE) of each trial is plotted against the trial number. Each point in Figure 4. 10 is the average over ten subjects’ MSE (see eqn (2), our measure of playback position error from the expert’s path) for a specific trial. The standard error bars are also shown in Figure 4. 10, to indicate the variance in the MSE results.
Table 4.1: Mean of the MSE for the Seven Trials of the Two Group

<table>
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<th>Group</th>
<th>Mean</th>
<th>Std. Error Mean</th>
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</tr>
<tr>
<td>1</td>
<td>2</td>
<td>10.5877</td>
<td>1.46517</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>17.5068</td>
<td>2.12875</td>
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<tr>
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<td>2</td>
<td>9.1282</td>
<td>.84554</td>
</tr>
<tr>
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<td>1</td>
<td>15.4140</td>
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<tr>
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<td>2</td>
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</tr>
<tr>
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<td>.67366</td>
</tr>
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<td>2</td>
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<td>.52570</td>
</tr>
</tbody>
</table>

4.2.2 Discussion

From the Figure 4.10 results we see that users generally improve in tracking the expert’s path with repeated trials. (The group without passive mode 1 playback training improved at a higher rate).
We also see that the group that was trained using the passive playback mode 1 (mode) performed much better, with regard to lower position MSEs, than the group without this passive playback training. Further, the MSE variance in the group with mode 1 training is lower than that of the other group.

To ascertain the significance of our results (to test whether the differences between treatment groups in the average Figure 4.11 MSEs are statistically significant), the Figure 4.11 data was analyzed using a repeated measures analysis of variance (RMANOVA) with trial as the repeated measure. The significance level was set at $P < 0.05$. Post hoc analysis was done using the Bonferroni test. Trials 2 through 7 all turned out to be significant using this conservative metric. The first trial was on the borderline of being significant.

Since the group which did both modes had more trials than the other group, we compared the first, second and third trials of the group which did both modes of playback, with second, fourth and sixth trials of the group which did only mode 2 of the Two Mode playback system (Figure 4.12). To test the significance, the data of figure 27 was analyzed using repeated measure analysis, and we found out that the two groups responded differently across trials. Groups 1 and 2 were significantly ($P < .05$) different for all trials.
From our results we conclude that the passive mode 1 playback training is beneficial to lower-position-error trainee performance in tracking an expert’s path during an example palpatory diagnosis task via active playback mode 2. Now, the question for our experiments in the near future is “Does the active playback mode 2 (complete with passive mode 1 training) improve the trainees’ performance with regard to palpatory diagnosis with the Virtual Haptic Back?” This, then, leads to the further question “Does practice with the Virtual Haptic Back (including modes 1 and 2 playback training) improve trainees’ palpatory diagnosis skills with real patients?”

4.2.3 Mode 1 Position Playback Evaluation

The position MSEs and standard error bars of Figure 4.11 help in showing how faithful the overall mode 2 active position playback is. But we have not yet considered
mode 1 passive playback errors. In Figure 4.12, the red curve represents the recorded positions and the green curve shows the path traced by the PHANToM in an example mode 1 position playback (performed passively by the expert who generated the test path for the mode 2 experiments of Sections 4.1 and 4.2). For black & white printouts of this thesis, the solid red path is darker than the green path in Figure 4.12. It was observed that the two lines were close throughout the entire motion, so the position error is fairly evenly spread. The expert generally experienced mode 1 passive position playback errors $MSE < 4 \ mm$; the lowest error recorded was $MSE = 0.264$. This indicates that the mode 1 PD position controller is performing well, generally much better than can be expected from the mode 2 position playback provided by the subjects actively following the expert’s path. Of course, the higher error of mode 2 may be worth it considering haptics is enabled for mode 2, while haptics is not enabled for mode 1.

![Figure 4.12: Playback and Recorded Paths](image-url)
5. Playback Using the Dual Handed Palpation System

The concept of playback was extended to dual handed palpation using two PHANToMs (Figure 5.1). This section describes the implementation of the Two Mode playback system for the dual handed VHB simulation. Only the Two Mode Playback System has been implemented for the dual handed palpation, since it is superior to the Combined Playback System.

5.1 Mode 1 (passive)

Two instances of the forcefields (one for each finger) were created and were forced to follow the recorded expert’s path using a PD controller. The force fields and the PHANToM tips are initially located at the initial expert path points. The force fields centers are then shifted to the next recorded positions. As this is done the driving forces (Equation 1) act on the PHANToMs. The force fields are shifted to next recorded positions and this loop repeats at a rate of $1000 \text{ Hz}$. 

5.2 Mode 2 (active)

In this mode two target balls trace the recorded expert’s paths and the user has to follow them in all three dimensions. The $XYZ$ coordinates are read from the recorded position file and the target balls traces the points. To help the trainees play back the $Z$ component (depth into back), two rectangular bars are used, that increase in length if the position error in the $Z$ direction is increased (Figure 5.2). The students must follow both the target balls actively. They will feel approximately what the expert felt if the position errors are kept small.
Figure 5.1: PHANToMs for Dual-Handed Palpation

Figure 5.2: Active Mode 2 with Target Balls and Z Error Bars
6. Conclusions and Future Work

This thesis has presented implementation and investigated performance for our combined position/force PHANToM haptic interface playback system and Two Mode playback system, for student training in our Virtual Haptic Back Project at Ohio University.

For combined position/force the experiments studied our two important playback parameters, the spring stiffness $k$ and the sphere radius $r$ where no there is no attractive force. For playback, high $k$ and low $r$ were found to be desirable for low position error. However, $k$ and $r$ have little effect on force errors; these were found to be small regardless of $k$ and $r$. Tradeoffs were discussed: if $k$ is increased too much or $r$ is decreased too much, in an attempt to reduce position errors, an undesirable, potentially unstable haptic buzzing results. The playback system was investigated with and without the human finger, plus with and without the force playback (without and with the haptics model enabled). It was acknowledged that the $k$ and $r$ values may change given different models and possibly by using a PD controller in place of the current P controller for position playback.

Since it is impossible to develop a playback system that can simultaneously playback both position and force accurately, we developed the second playback system called the ‘Two Mode Playback System’. In this Playback mode 1 uses a PD controller to cause the user’s finger to trace out the path of an earlier-recorded expert’s motions during example palpatory diagnoses. Mode 1 is called passive since the trainee’s finger is passive (while the system is actively replaying position). In mode 1 there is no haptic feedback since the haptic interface motors are already used to play back position.
Playback mode 2 uses graphical cues for the trainee to actively follow, replicating the recorded expert’s motions via trainee arm, hand, and finger motions. In mode 2 the Virtual Haptic Back haptics model is enabled (since the haptic interface motors are now free to be used) and the trainee feels approximately what the expert felt during the recorded motion. We are investigating whether our two-mode playback system is beneficial in palpatory training applications.

The experiment presented in this thesis tested whether playback training with passive mode 1 improves performance during active playback mode 2 trials. Our results show that the group with passive mode 1 training performed significantly better (with regard to lower playback position errors) than the group without passive mode 1 training. Therefore, in our future work in this area (testing if playback improves performance with the Virtual Haptic Back and then whether practice with the Virtual Haptic Back improves palpatory diagnosis performance with real patients), we will use both playback modes for the groups that use playback in their experiences.

We believe that our two-mode playback system can significantly improve virtual training applications based on this first step in implementation and evaluation.

A future goal is to integrate two PHANToM interfaces, including playback, within the Virtual Haptic Back. Users can then use their thumb and forefinger (or fingers from two hands) to palpate as they do in the real world. Another near-term goal in the project is to perform playback experiments with trainees to determine the potential impact of our playback system on learning palpatory diagnosis tasks using our Virtual Haptic Back.
References


Appendices

Appendix A

Manual for Using the Playback System

This appendix explains how to use playback system.

When the Two Mode Playback program is run:

1. A dialog box appears asking whether you want to record a new tactile examination for playback or would you like to select a recorded path.

2. If you selected to record, then the user should enter the file name. Otherwise select the file that you want to playback.

3. If the user had recorded a file then, if he wants to play it back then run the program again and select the file for playback.

4. When the playback is running you can shift between the modes (model 1 and Mode 2) using the “Mode” button.

5. User can also make the playback restart using the “Reset” button.
Appendix B

Programming Details

Playback systems were programmed using C++, openGL, ghostGL and Visual C++. Visual C++ Class Wizard is used to create dialog boxes to get the user’s input whether he wants to record or run a recorded file.

To record a file Standard Template Library linked list is used. The users positions and forces are stored in binary format. If the user has selected to record a file then the PHANToM’s position and forces are read using the ghostGL commands.

Combined Playback system

When the user selects to run a recorded file the positions and forces are read from the recorded file. Then the driving force is calculated using the position of the PHANToM.

The driving force is updated at 1000 Hz. The calculateForceFieldForce function of gstForceField class provided by ghostGL is overloaded to return the appropriate driving force. The forcefield is translated at 1000 Hz. The corresponding recorded force is also sent to the PHANToM. The haptics model is enabled or disabled using the ghostGL commands for each haptic object.

Two-Mode Playback System

This mode has two buttons in the toolbar, namely Reset and Mode. This mode has an openGL error bar and a target sphere. The target sphere follows the recorded file and the error bar grows in length if the distance between the PHANToM’s position and the target sphere in the z direction increases. The reset buttons makes the playback to restart.
The code for the visual cues is written in a separate function which is called at 30 Hz from the update graphics function.

**Playback draw**

The program called playback draw, draws the recorded and playback paths. Appropriate line widths and colors are selected using openGL commands.