Design of a Three Degree of Freedom Force-Reflecting Haptic Interface

by

Thomas Harold Massie

Submitted to the Department of Electrical Engineering and Computer Science
in partial fulfillment of the requirements for the degree of

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I would like to thank the following people for helping me complete this thesis:

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Contents

Chapter 1

Introduction

The primary focus of robotics research has traditionally been autonomous systems - those which operate without human supervision or interaction. However, the design of robotic systems which actively interface with humans is gaining much attention. These new interactive systems promise to expand the abilities of humans, by increasing physical strength, by improving manual dexterity, by augmenting the senses, and most intriguingly by projecting human users into remote or abstract environments. These remote environments can be real. For example, using telepresence a doctor can be projected into his patient's body. These environments can be artificial. For example, a doctor may operate on an artificial patient simulated within a virtual environment.

These new systems can be differentiated from traditional attempted simulations (e.g. graphical flight simulators) and remote controls by the fact that these new systems provide force-feedback. If the user is to be convinced that he or she is actually operating in a remote environment or simulated world, visual stimulation and auditory cues are not sufficient. Of the five senses, only one provides a two way interface with the environment - that is touch. Using touch, a human can affect the environment while at the same time realizing the effect. This mode of direct feedback is essential for transporting the user into remote environments.

In this thesis, I addressed the creation of a new system which provides the necessary force-feedback to allow users to interact convincingly with artificial or remote environments. Specifically, the purpose of this endeavor was to design, construct, and evaluate a three degree of freedom force-reflecting haptic interface. In its intended use, an operator places his or her finger in the device and interacts with surfaces and objects in a virtual environment simulated within a computer. The device provides force feedback, allowing the user to "feel" objects within the virtual environment.

1.1 Overview

Chapter 2 focuses on design criteria and describes the general qualities that are desirable for a force reflecting master. A set of objective design parameters necessary for producing a master with these qualities is then developed. This is followed by a discussion of the design decisions made in order to achieve these parameters.

Chapter 3 evaluates the performance of the device in terms of the objective design goals. A more subjective evaluation of the haptic interface is presented in Chapter 4. The subjective review of the joy-stick is based on comments from users who have experienced interactions with the virtual environment, using the device.

An evaluation of the objective design goals and their relative importance for producing a convincing force-reflecting interface is presented in chapter 5. Finally, possible improvements and applications of the device are discussed.

Chapter 2

Design

In any design process, it is first necessary to establish design criteria. For this device, the criteria were obtained by first envisioning the perfect force-reflecting haptic interface. With the ideal device being defined, it was possible to qualitatively describe those characteristics of proposed devices which yield performance close to that of the ideal. It was then necessary to rank these criteria in order of relative importance and to assign more quantitative values to each parameter.

The second section of this chapter describes the final design of the device. Justifications for many of the design decisions are provided in terms of the criteria described in the first section.

A photograph of the final device is shown in figures 2-1, 2-2, 2-3, on the following pages. It was decided that the device should be coupled with a user's finger tip. The tip of the index finger alone is a sensory device which is arguably as rich as the human eye, nose, tongue, or ear. Two interfaces between the user and the device were constructed. The first, a thimble worn on the index finger, allows the user to simulate probing with his finger. The second interface, a slender, pencil-like tool held by the user, allows the user to interact with the environment as he would with a pointed instrument.

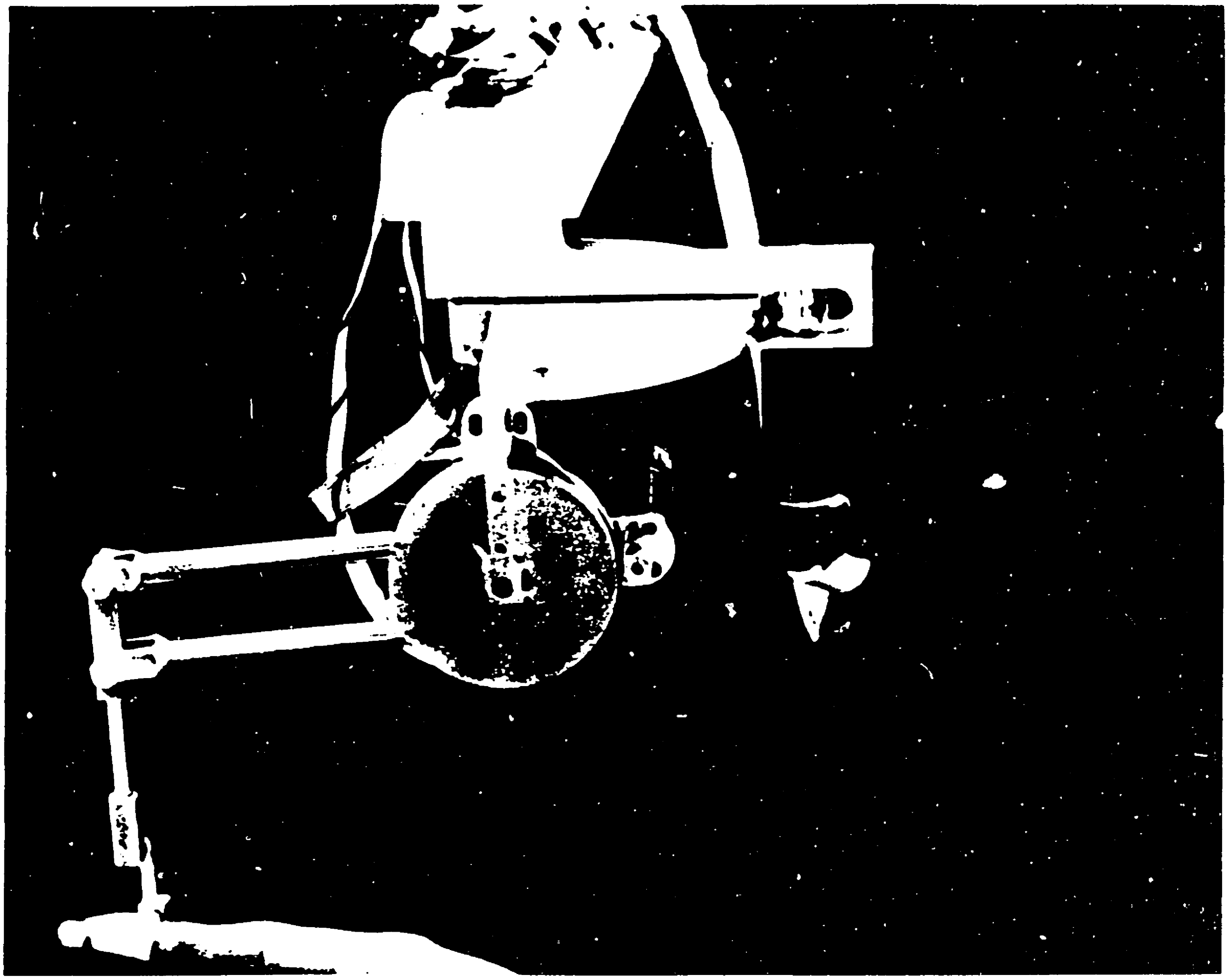

Figure 2-1: Force-Reflecting Haptic Interface as Built

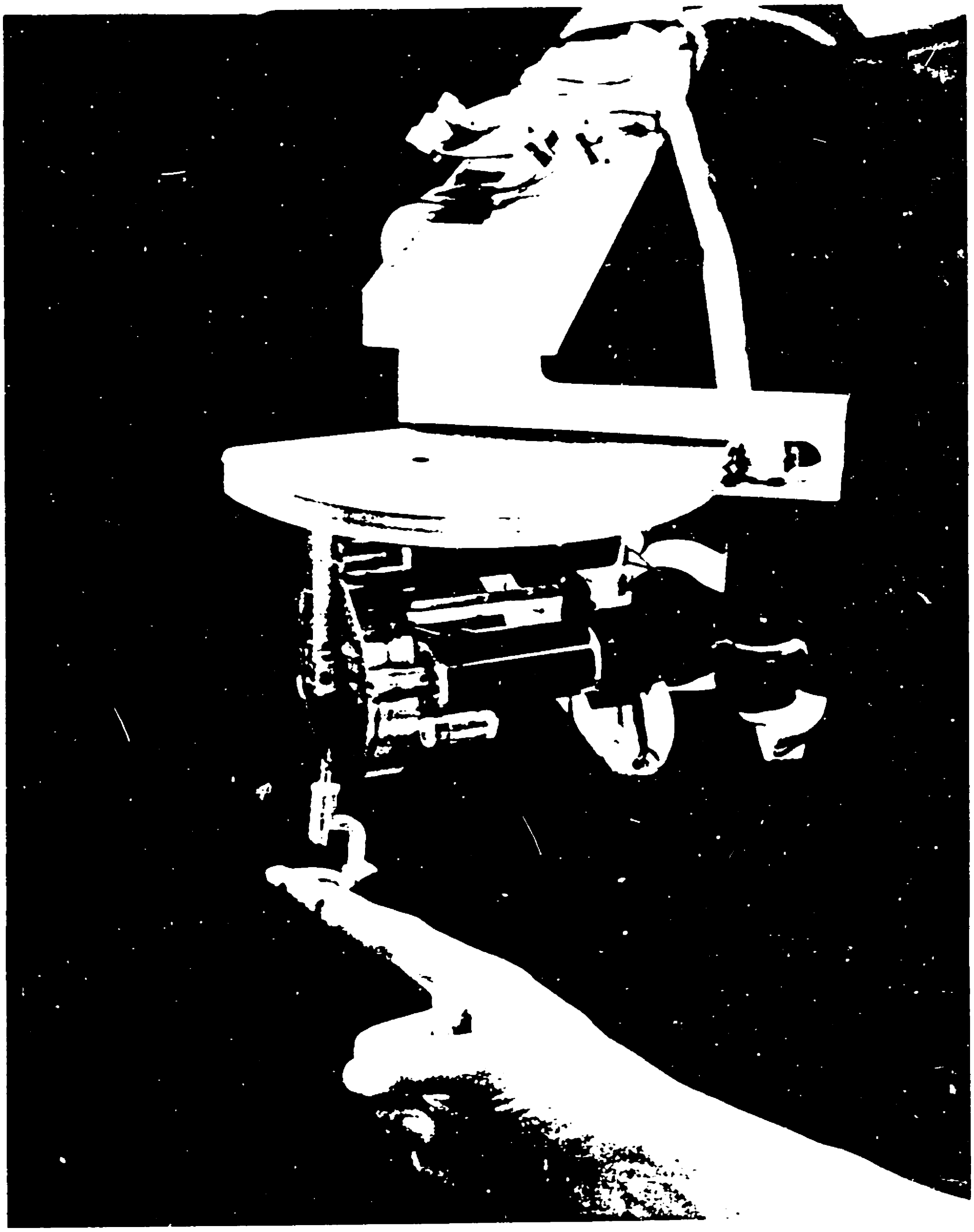

Figure 2-2: Force-Reflecting Haptic Interface as Built

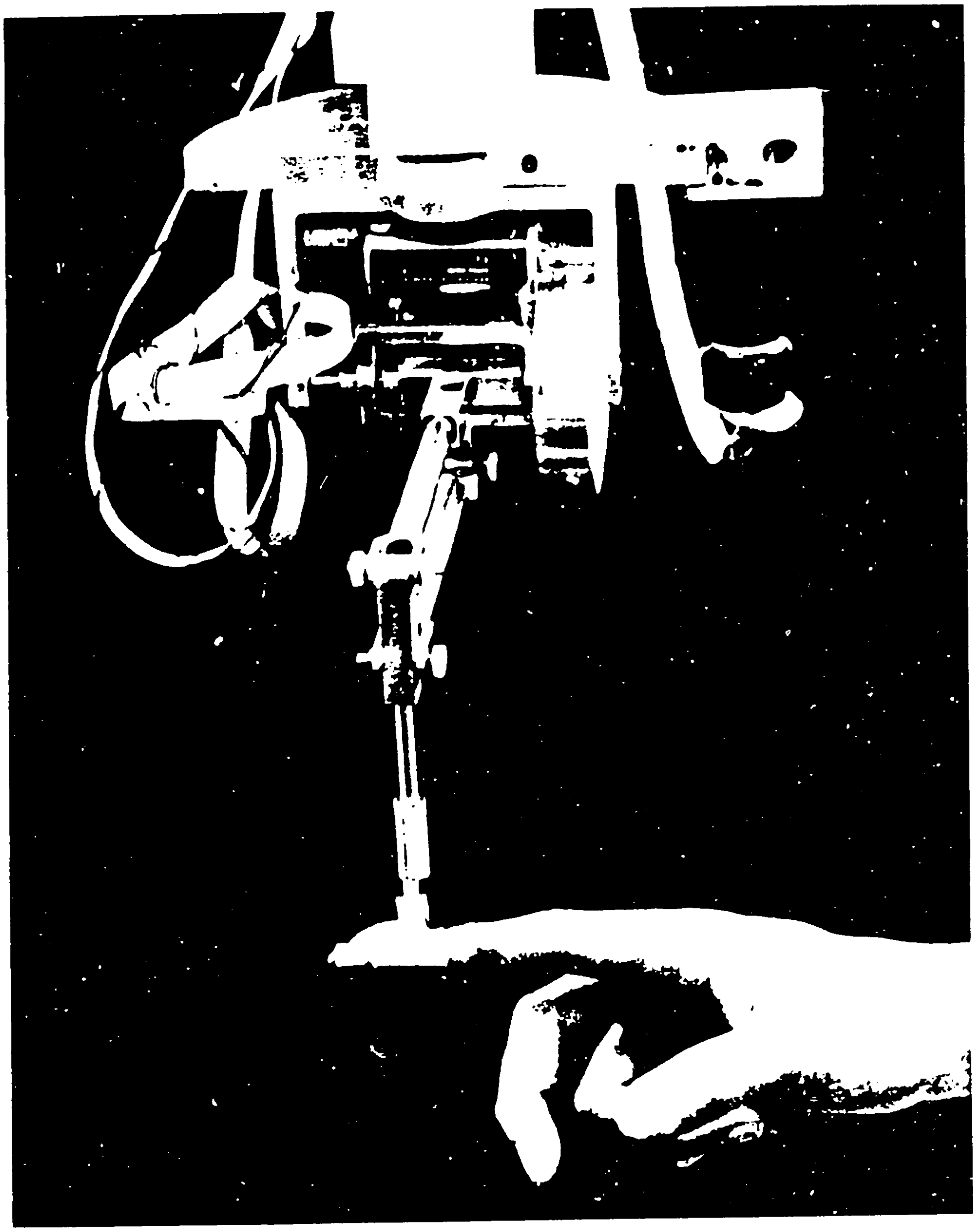

Figure 2-3: Force-Reflecting Haptic Interface as Built

The human haptic system is composed of subsystems that enable tactile and kinesthetic senses as well as motor actions[4]. Some attempts at stimulation of the tactile receptors in the human finger tip have been made in previous research [1]. However, this project is concerned only with the application of force vectors upon the user's finger. Effective tactile stimulation is difficult due to the high density of receptors in the human skin. Adding a device for tactile stimulation would have compromised the performance of the force-reflecting interface.

Previous attempts at constructing force reflecting interfaces have generally fallen into one of two categories - exoskeletons and externally grounded joysticks. Exoskeletons are worn by the user and can often exert forces at several locations along the arms and or fingers[3]. There are more constraints in the design of an exoskeleton device, as the structure must attach to several locations on the human body and the exoskeleton joints must be co-located with human joints. Counterbalancing such structures and designing stiff, uncoupled transmissions for them is difficult. In the interest of minimizing complexity and maximizing performance, the general design for this project was chosen to be an externally grounded joystick.

A force reflecting interface should have the minimum number of degrees of freedom necessary to maintain task functionality[2]. The human finger tip has six degrees of freedom as viewed from an external reference frame. Three values can completely specify the location of the finger tip and three values specify the rotations of the finger tip. If the finger tip is viewed as a point in space, only three values are necessary to completely describe its state. Designing a device with three actuated degrees of freedom is much simpler than designing a device with six actuated degrees of freedom. Treating the finger tip as a point in space also greatly reduces the complexity of modeling interactions in a virtual environment. For these reasons, a design with only three actuated degrees of freedom was chosen.

2.1 Design Criteria

2.1.1 The Ideal Force-Reflecting Haptic Interface

The purpose of a force-reflecting master is to give the user a sense that he or she is touching an object which is not actually within the vicinity of the user. This "virtual" object can be represented within a computer or it can be a real object, being manipulated by a slave device.

If the haptic interface were ideal, the user would not realize that he was wearing such a device. (A Turing test of sorts for virtual interactions.) Specifically, a user would not be able to distinguish between touching a real object and touching a virtual object with the device. Also, the device would not encumber the user. That is, the ideal interface would exert no external forces on the user when he is moving in free space.

Hard surfaces, such as walls would feel as stiff with the device as they do in real life, even when contacted at a high velocity. Corners of solid objects could be made to feel crisp. Compliant surfaces would feel springy. Users wearing the device would be able to distinguish between surfaces of different textures.

2.1.2 Desirable Criteria for an Effective Interface

With the ideal force-reflecting device described, a list of necessary traits for such a device can be developed. Because none of the following traits can be absolutely achieved, they shall be expressed in relative terms.

The device should have very little backdrive friction. Friction not only adds noise to the forces that the device attempts to reflect back to the user, it also creates a cue to the user that the virtual world is artificial. In the extreme case, friction can cause the user to fatigue after using the device for long periods of time.

The device should have a low inertia. The inertia of the device is not a problem when the user moves slowly. However, when the user accelerates or deaccelerates quickly, the inertia of the system will give the user the undesirable sensation that he or she is wearing an external weight. Additionally, the inertia of the device also limits the speed at which the device can respond.

The device should be statically balanced at all points within its operating space. As with friction, an external force created by gravity acting on some unbalanced portion of the device can pollute the forces that the user experiences. Also, a constant offset in force can quickly lead to fatigue for the user. The device could actively compensate for imbalances in the mechanical structure, however this would require compromising the dynamic range of the actuators in the system.

There should be very little backlash in the transmission of the device for several reasons. If the location of the endpoint of the device is to be calculated from the position of the motors, the error in the calculated position will be equal to the play in the transmission. Also, backlash introduces a discontinuity in the force transmitted from the motors to the the endpoint. While in the region of backlash, the user does not feel the load of the motor on the other end of the transmission. However, as the user moves (or the motor moves) the device out of the region of backlash he or she will experience a hard transition as the force of the motor is once again engaged. The non-linearities introduced by backlash also tend to destabilize some servo algorithms.

A stiff structure and transmission is necessary if the device is to simulate hard surfaces. The compliance of the structure and transmission sets an upper bound on the stiffness of surfaces which can be represented with the joystick. The stiffness of the control closed around the motors should also be high, however this is more a function of the particular control loop implemented, the resolution of the position resolvers, and the apparent inertia seen by the motors.

The position resolution of the device should be high for two reasons. Obviously a high resolution will enable the device to reflect finer position details of a virtual environment. Also, the resolution of the resolvers sets a limit on the stiffness of the control loop which can be closed.

The device should be able to exert a force large enough, so that the user can discover the stiffness of a surface without saturating the motors. This insures that the user will perceive the wall as immovable. A high maximum force will also enable the device to display impact force transients more accurately in the virtual environment (as when the user strikes a virtual wall). The maximum force that the device can exert should also be viewed in relation to the backdrive friction inherent to the device. It is desirable to have a high ratio of maximum force exertable to backdrive friction as this will determine the dynamic range of forces the device can exert.

Finally, the device should have a large range of motion. The user should be able to perform tasks within the virtual environment without being overly constrained to a small workspace.

2.2 Design Specifications

As with any design effort, the criteria are interrelated. Changing one parameter will necessarily change one or more other parameters. Additionally, many of the specifications are dictated by available technology. For this device, an attempt was made to translate several of the criteria into quantitative specifications.

2.2.1 Maximum Exertable Force

The average maximum exertable force for the index finger is 50 newtons and a previous study suggests that 40 newtons would be a good design maximum for a telerobotic handmaster[5]. For this thesis, tests were conducted to determine if a device with a lower force capability could provide acceptable performance.

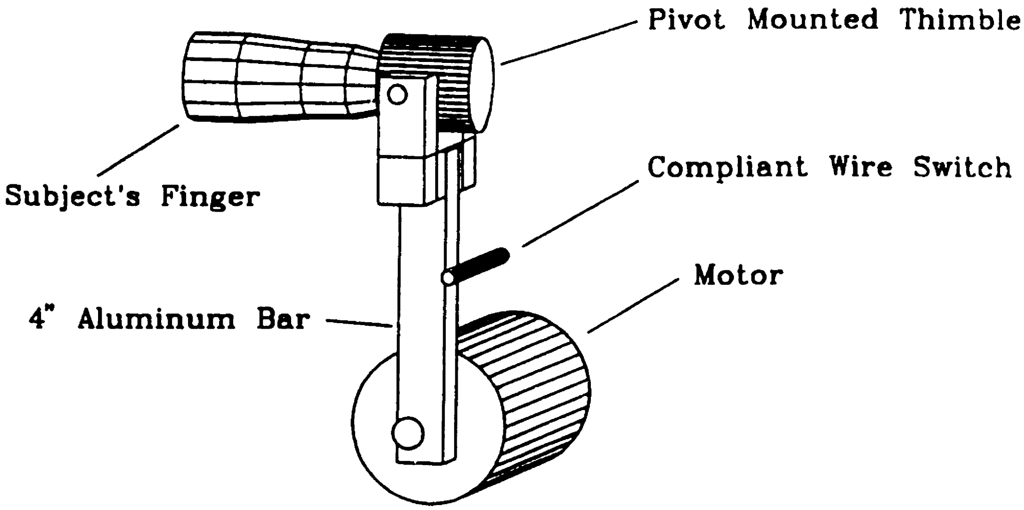

Figure 2-4: Apparatus for Determining Maximum Exertable Force

The apparatus shown in figure 2-4 was constructed and two subjects were asked to push against the device until the contact switch closed. After the switch closed, the device would exert a force against a subject's finger. The subjects were asked if this force was large enough to feel as if there was an immovable object located in front of their finger.

Three different forces (created with three different motors) were evaluated, 29 newtons, 11 newtons, and 1.4 newtons. Both subjects agreed that 1.4 newtons of force could not create the illusion of a solid wall. Because the apparatus provided a step change in force, it was hard to evaluate 29 newtons of force (The apparatus produced a violent kick against the subject's finger when passing through the transition from zero force to 29 newtons.) Both subjects agreed that 11 newtons should be sufficient for creating the static illusion of a solid wall.

Based on the subjects' experiences, 11 newtons was chosen as the maximum force exertable by the force-reflecting interface. Not only did it seem that 11 newtons would be sufficient to create the illusion of a wall, but also that a device capable of exerting more force could pose a possible hazard to a user's finger.

2.2.2 Backdrive Friction

As stated earlier, it is desirable to keep the ratio of maximum exertable force to backdrive friction as high as possible. There are at least three sources of backdrive friction - the friction force in the bearings of the structure, the friction of the transmission, and the friction in the actuator. The friction in the structure and transmission can be made very low, therefore the current state of motor technology places an upper limit on the ratio of maximum exertable force to friction that can be achieved. Previous research into motor technologies indicated that a ratio of 30:1 was a realistic goal for open loop control. Although the ratio of maximum force to friction force may be fixed by the choice of motors, the particular operating range of the forces is determined by the transmission ratio.

2.2.3 Inertia

By wearing various weights upon the finger and performing certain tasks, it was empirically determined that the apparent mass felt by a user wearing this device should be less than 100 grams.

The apparent mass felt by the user is proportionally related to the inertia of the structure plus the reflected inertia of the motor. The reflected inertia of the motor armature is proportional to the transmission ratio, N, squared.

2.2.4 Backlash

Humans are extremely adept at discerning small changes in position with their fingers. A transmission with a backlash that resulted in a positional variation of more than 0.01 inches would not be acceptable.

Also, the force non-linearities created by backlash in the transmission are difficult to model and therefore make force control difficult. For this reason, the system should have zero-backlash.

2.2.5 Stiffness

The stiffness of the structure, the stiffness of the transmission, and the stiffness of the servo loop, determine the overall stiffness and bandwidth of the device. The stiffness of the structure and transmission can be made very high. The transmission ratio, N, for this particular device was fairly low (between 4 and 20) therefore the limiting stiffness for this device was that of the servo-loop.

The maximum stiffness achievable with the stable servo-loop is a function of the inertia of the device, the impedance of the user's finger attached to the device, the transmission ratio, the servo rate, and the encoder resolution. The transmission ratio is the easiest of these factors to vary.

2.3 Final Device Design

2.3.1 General Layout

As previously stated, this design incorporates three passive degrees of freedom and three actuated degrees of freedom. This allows the device to exert force vectors on the finger tip without exerting torques. A sketch of the device kinematics is shown in figure 2-5.

The device can exert a cartesian force vector on the user's finger, by using the motors to exert a torque upon the joints. The computer calculates the required motor torques by multiplying the cartesian force vector by the transpose of the jacobian.

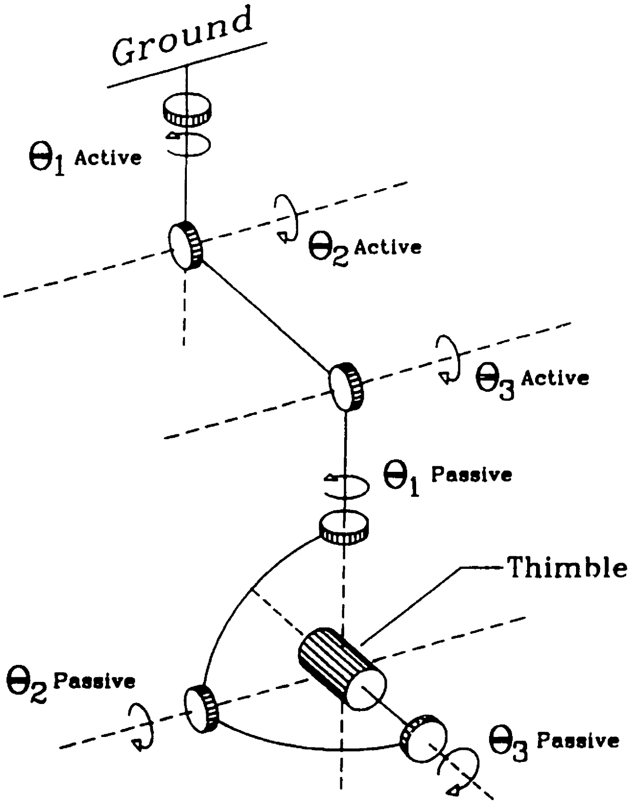

Figure 2-5: Kinematic Representation of the Device

2.3.2 Passive Gimbal

A mock-up of the device was first fabricated with wood. The gimbal on this mockup was rather bulky, but provided some insight into what the final design should look like. A quarter gimbal design, with a pair of bearings at each joint was synthesized as shown in figure 2-6. As with the entire design, an effort was made to keep the mass of the gimbal very low.

2.3.3 Workspace

It was initially unclear what the allowable range of motion for this device should be. The passive wooden mockup of the device helped to establish this range. Previously, it had been decided that the range should be at least as large as the range of the tip of index finger with respect to the hand. Also, it had been decided that the range

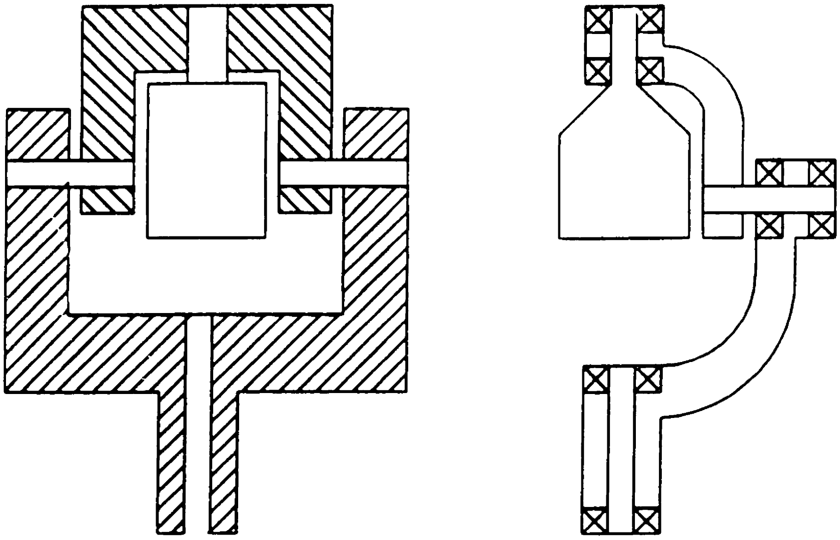

Figure 2-6: Wooden Mockup (left) and Final Design (right) of the Gimbal

should be smaller than the range of the tip of the index finger with respect to some fixed location of the elbow (for example if the elbow were located upon the table).

The mockup which was built allowed for complete range of motion of the index finger and permitted very limited movement of the wrist. Through trials with the mockup, it was discovered that users often preferred to rest the forearm on the table and use movements of the finger, knuckle, and wrist joints to position the tip of the finger. For this reason, users often tried to exceed the limits of the workspace when wearing the mockup. It was decided that the final design should have the first actuated joint located directly above the human wrist joint and allow users to move their wrist, knuckle, and finger joints to all extremes without exceeding the workspace of the device.

2.3.4 Motors

Given a desired range of motion, a desired maximum exertable force, and a transmission ratio, the necessary peak torque for the motors can be found. In selecting the motors it was assumed that the transmission ratio would be on the order of 5:1. Suitable motors, weighing 130 grams with a peak torque of 24 newton-centimeters were obtained from Maxon, Inc. The motors use an ironless core technology which reduces torque ripple and keeps the armature inertia low. The highest resolution encoder available for the selected actuator was the Hewlett-Packard 5310 model at 2000 counts per revolution.

2.3.5 Transmission

One of the design criteria was that the transmission should have zero backlash. Several readily available gear reductions were examined, but all had at least 0.2 degrees of backlash. For the dimensions chosen, this translated to about 0.02 inches of variation in the position of the gimbal, given zero variation in the motor position. These reducers clearly did not meet the established specifications for this device.

A "direct-drive" design that would need no transmission reduction was considered, but this required using motors with a higher stall torque. This meant the motors would have been larger in both volume and mass. No sufficiently small motors were located that could produce enough torque for a direct drive system.

It was decided that only a cable transmission could meet the zero backlash specification with very little friction, while at the same time achieving a transmission reduction. Because the cables can be pretensioned, the backlash in a cable transmission can be made zero.

In spite of their benefits, cable reducers are not widely used in robotics. This is probably due to the subtle considerations which must be included in their design. A list of those considerations used for this transmission design is given below:

1. The routing of cables should be made such that the radial forces on motor and pulley bearings are minimized.

2. Cables which are wrapped around pulleys more than 360 degrees require a finite pulley width, because they "walk" across the pulley as it spins.

3. The tension which a drive capstan can maintain on a cable is proportional to $e^{Fc \times \theta}$, where Fc is the coefficient of friction between the cable and capstan and theta is the number of degrees that the cable is wrapped around the capstan.

4. Cables have a finite minimum pulley radius around which they may travel without creating friction and being significantly fatigued. The minimum radius for 0.028 inch cables used for this project was about 0.2 inches.

5. Transmissions should avoid excessive free lengths of cables over long spans. Long lengths of cables introduce more compliance into the transmission. Additionally, pretensioned lengths of cables, act as energy sources which can lead to unwanted resonances at certain frequencies.

6. It is often helpful to add a spiral groove to capstans. This insures that the cable travels in the same manner each time and that wraps of the cable do not scrape each other. This groove also effectively increases the friction coefficient between the cable and capstan which is desirable.

Location of the motor to actuate the first axis was not difficult, as this motor was stationary and its mass did not contribute to the inertia of the device. Several scenarios were considered for locating the motors to actuate the second and third axes. The challenge was to locate the motors such that they contributed the least to the rotational inertia of the device about its joints. After considering several designs, a very elegant solution was conceived. (Please refer to figure 2-7.)

In the final transmission design both motors act as counterweights so they passively balance the structure at all points within the workspace. This solution for

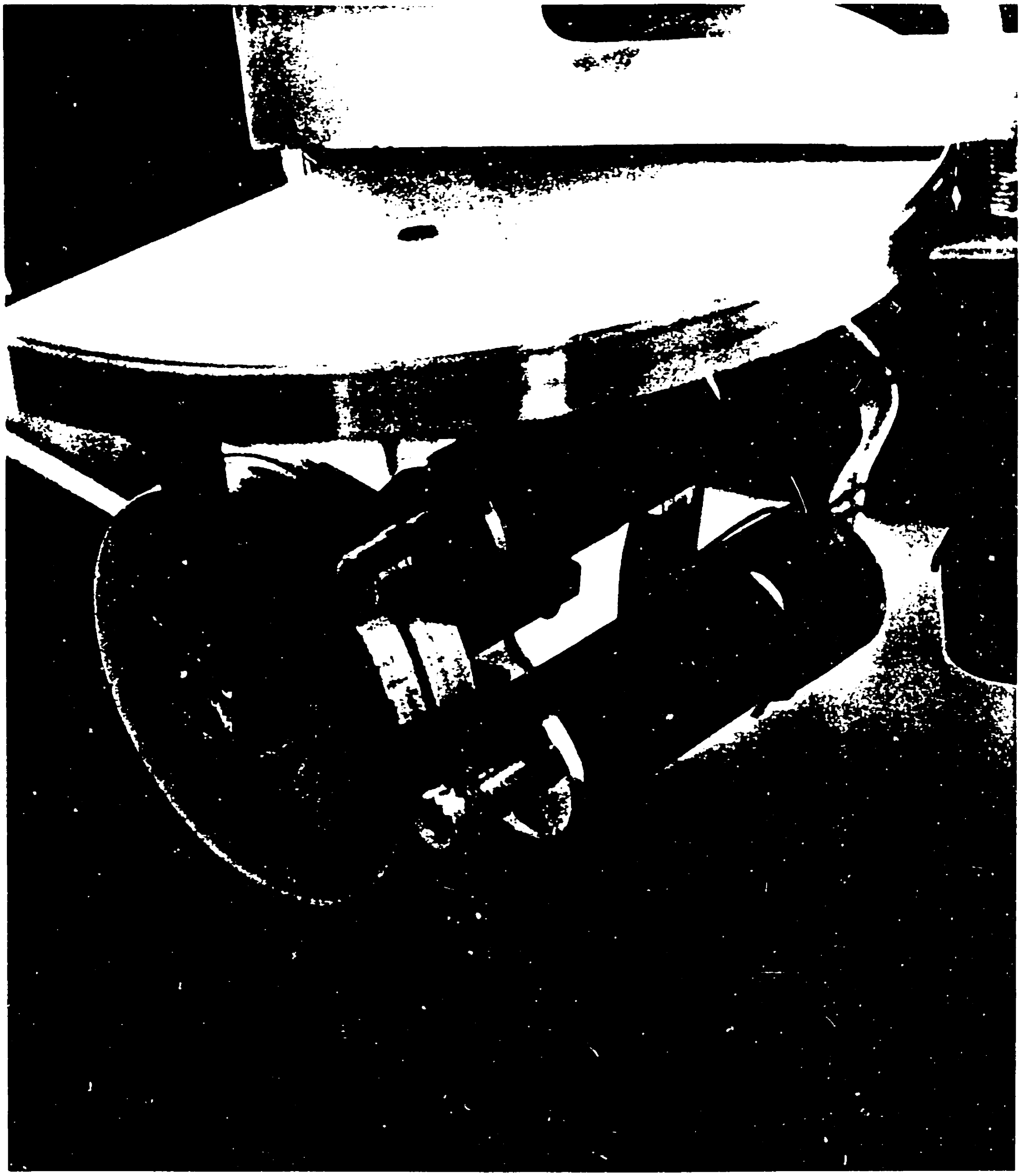

Figure 2-7: Cable Sharing Scenario - Motors Serve as Counterweights.

motor placement is nice because it satisfies the criteria that the structure should be statically balanced, without adding any extra dead weight.

Only one cable is used for both motors. This simplifies the design greatly, as it is only necessary to install and pretension a single cable for the two axes. Also, the cable is wrapped so that pretensioning it adds no axial loads to the motor bearings.

The size of the drive capstans and the size of the large pulley which the motors drive on, were determined by several factors. Their relative sizes were chosen to maximize the gear ratio while still satisfying the following constraints. The large pulley had to be large enough so that the motors could move within 45 degrees of each other without touching. Also, the large pulley had to be small enough that it did not block the motion of the user's hand. It was also desirable to keep the radius of the large pulley small so that the rotational inertia of the two motors about the base axis was small. The radii of the capstans were chosen to be the minimum allowable for 0.028 inch cable. The reduction for this transmission turned out to be 7.5:1.

After the locations of the two motors using the same cable were determined, the range of motion for the device was again modified slightly so that the device would be statically balanced.

The transmission for the motor driving the base axis was a bit simpler to calculate. The value of the reduction for this axis was made slightly larger for two reasons. The inertia and friction of the structure about the base axis was considerably larger than that of the other two axes. It was necessary to compensate the transmission reduction for the larger inertia so that there would not be a loss in bandwidth about the base axis. Also, the friction in the bearings of the structure was higher than that caused by the motor for this axis, so increasing the transmission ratio would not increase the backdrive friction considerably. Therefore, the transmission ratio for this axis was increased to 8.75:1. The motor mount is adjustable so that this ratio can be increased to 11:1 if need be.

Chapter 3

Objective Analysis

What follows is an evaluation of the actual device in terms of the specifications set forth in chapter 1.

3.1 Maximum Exertable Force

The maximum exertable force of the device was measured with the device located in the center of the workspace as shown in figure 3-1. The haptic interface was capable of exerting 8.5 newtons of peak force along the x and z axes. Due to a slighter higher transmission ratio for the first motor, a peak force of 9.5 newtons was possible along the y axis. It should be noted that these peak forces were thermally limited. That is, after 3 seconds of saturating the motors, the force dropped by 15 percent and the motors became very warm.

These maximum forces are approximately 20 percent lower than those set forth in the specifications.

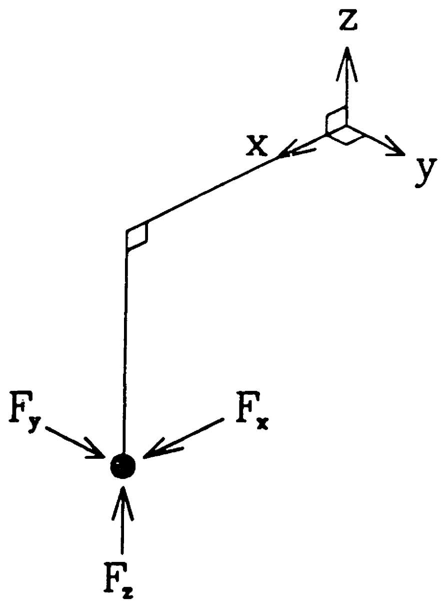

Figure 3-1: Static Position Used for Measurements

3.2 Backdrive Friction

The stiction of the haptic interface was measured with the device positioned as in figure 3-1. The stiction along the x and z axes was found to be 0.03 newtons, while the stiction along the y direction was found to be .17 newtons. The higher value along the y direction was due to the fact that bearings of the first axis of rotation (the base) of the device support most of the weight of the device.

Dividing the maximum forces exertable by the stiction values gives us the ratios described in the chapter 2. Along the x and z axes this ratio is 283:1. Along the y axis this ratio is 56:1. The ratios exceed the design goal of 30:1. Using higher quality bearings, it may be possible to lower the friction along the y axis.

3.3 Inertia

The apparent mass as felt by the user is not constant at all points within the workspace due to geometric changes as the device moves. In fact, as x and y go to zero, the device nears a singularity, and apparent mass of the device in the x and y directions approaches infinity. With this in mind, the apparent mass of the device as felt by the user was calculated for the device at the nominal position in the center of the workspace as shown in figure 3-1. In the x and z directions, the apparent mass was found to be 60 grams. In the y direction, the apparent mass was calculated to be 95 grams. For the position shown, the device is within the specifications (apparent mass < 100 grams).

3.4 Balance

The device was statically balanced to within 10 grams for all points within the workspace. This amount of imbalance is small and can be compensated for with the motors.

3.5 Backlash

Because the transmission consists of a four-bar linkage with preloaded bearings and a pretensioned cable reduction, the backlash for this device is zero.

3.6 Stiffness

As predicted in chapter 2, the stiffness of the structure and transmission do not significantly affect the overall stiffness of the device. The stiffness is primarily a function of the gain of the servo loop. Presently, the limiting factor in setting this gain is the rate at which the computer can close a servo loop around the motors. At a servo rate of 1 KHz, the maximum achievable stiffness of the device is 16 newtons per centimeter. At a servo rate of 2 KHz a stiffness of 32 newtons per centimeter can

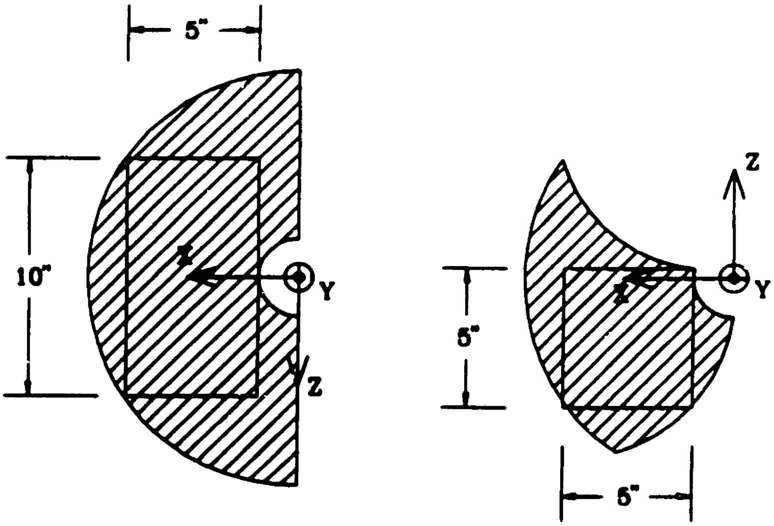

Figure 3-2: Effective Workspace of the Haptic Interface

be obtained. With more computational power or more efficient code, the device can be made stiffer.

3.7 Workspace

The device has a workspace as shown in figure 3-2. The workspace is such that, a user resting his forearm on a table, will not be able to reach the limits of the device. Although the workspace is not rectangular in nature, a box with dimensions of 5" by 5" by 10" would fit within the space.

Chapter 4

Subjective Analysis

Several simple virtual environments were created within the computer and ten subjects were asked to use the haptic interface to interact with objects and surfaces within the various environments. Their comments provided a basis for a subjective analysis of the device.

4.1 Description of the Virtual Environments

The simple virtual environments were composed of cubes and spheres of varying stiffnesses, sizes, and surface textures. The environments were created in software on a personal computer.

The first environment in which the subjects operated in was a box. The user's fingertip was constrained to remain inside of a virtual box with dimensions of 3" by 3" by 3". The motors exerted no torque (and thus no force) while the user's finger tip was located within the box. However, if the user attempted to move his finger beyond one of the planes defining the box, the device exerted a force (normal to the plane) against the user's finger. The force exerted upon the user's finger was made proportional to the distance by which the user had violated the plane. The constant of proportionality is known as the stiffness. It was possible to vary this parameter, thus making the walls feel more or less compliant.

The next building block created for the virtual simulations was a solid cube. Like the hollow box, the stiffness of the surfaces defining the cubes could be varied. The code was written so that up to 7 cubes of varying size and location could be located within the virtual workspace at one time.

Obvious extensions of the unit cube were then implemented. A cube was made to move back and forth within the environment, pushing the user's finger out of the way if need be. Another cube was made to have sinusoidal variations in surface height to simulate a rough surface. Finally, a non-stationary cube was assigned a mass and a viscous friction. Users could push this cube around in the zero gravity virtual workspace while viewing a graphic representation of the moving cube on the computer screen.

Spheres were implemented in much the same manner as cubes. When the user violates the surface of a sphere, a force is exerted on the user's finger in a direction normal to the surface of the sphere and proportional to the distance which the user has violated the sphere. As with the cubes, the stiffness of the spheres can be varied.

4.2 Description of Tests

Various combinations of the virtual spheres, cubes, and boxes were combined to create the environments that the subjects interacted with. For each environment, users were asked to try both the thimble and pencil attachments on the force-reflecting device. Most users mentioned that higher fidelity was possible when using the pencil to interact with the environment.

For the simplest environment, most users required less than ten seconds to realize that they were experiencing the inside of a box. Most described the walls as "fric-

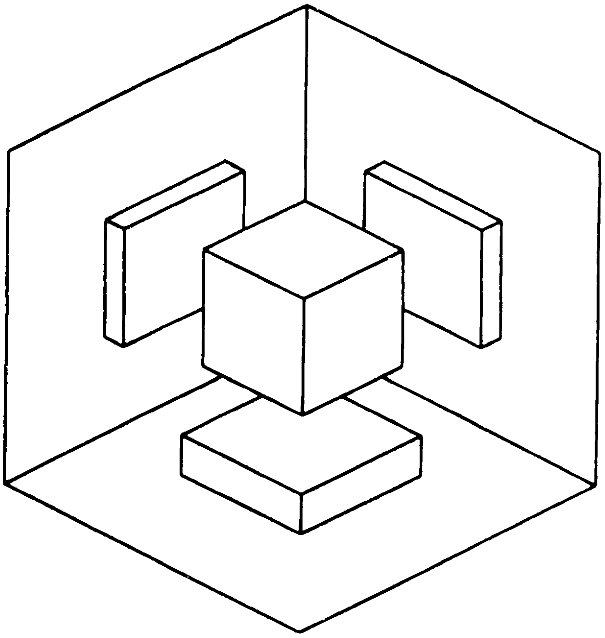

Figure 4-1: Partial View of Virtual Environment

tionless" and "smooth". One subject likened the experience of sliding along one of the walls as to that of "an icecube sliding on glass."

Having experienced the inside of a box, users were asked to explore more complicated environments like the one represented in figure 4-1. In this environment, a small stationary cube is floating in the center of the workspace. Small cubes also protrude from the walls surrounding the center cube. Subjects interacting in this environment easily located the cube in the center and described its edges as "sharp". Upon exploring the walls of the hollow box, users easily found the protruding cubes. One person described the experience as finding "something stuck in the wall." Another described the protruding cube as "a tile glued to the wall." Three subjects volunteered the fact that the tiles were not all of the same height. This was indeed true, as the cubes protruded from the walls a distance of about 0.3 cm to 0.8 cm depending on the particular cube.

In another experiment, users were presented with two cubes of the same size and stiffness. One cube was very smooth and the other had a simulated rough surface on the top and bottom. The subjects were asked to describe differences in the cubes. A surgeon using the device to stroke the rough cube[1] claimed that he felt as if he were "scraping bone." Most of the subjects described one cube as "rough" or "scratchy." In fact, three users commented that the surfaces even sounded rough. A close examination of this phenomenon revealed that a motor in the device did indeed make an audible sound as it vibrated to simulate the surface variations. This suggests that audible cues can be effective in augmenting the sense of touch in virtual environments.

Some subjects, not knowing what to look for, did not detect the differences in cubes until prompted to describe the textures. After realizing that the top of the cube was supposed to be rough, users were able to correctly identify the bottom of the cube as the only remaining rough surface in the virtual environment. Two users complained that the illusion of a rough surface was not complete, but instead it simply felt like the device was vibrating. This may be due to the lack of tactile information provided by the device, or it may be due to the fact that shear forces caused by the rough surface friction were not modeled in these experiments.

Next, subjects were presented with a cube that moved left and right with a periodic frequency of about one hertz. Most were surprised to find a non-passive object in their virtual environment. Asked to describe what he felt, one user incorrectly identified the moving object as a "rat." No visual representation of the object was shown on the computer screen, and several users searching with their finger for the object likened the experience to fishing.

Finally, spheres were introduced into the environment. Users correctly identified them as "round." Perhaps the most graphic description of the lower stiffness spheres would be "squishy eyeballs."

The sign of the force exerted upon users violating a sphere was changed, and miniature black holes or gravity wells were realized in the virtual environment.

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[1] the pencil-like handle was installed for this particular test

4.3 Interpretation of Results

The device is indeed capable of giving a compelling sensation of solid objects in a virtual environment. When asked to press hard upon the walls, users noticed a springiness. However when using a reasonable force (200 grams) users described the illusion of solid surfaces. As expected, most users never saturated the motors of the device by applying more than 100 grams of force to the thimble.

Both flat and spherical surfaces were successfully represented with the device, therefore it is reasonable to assume that more complicated shapes can be realized. In fact, the device should be able to represent the surface of any object for which there is a mathematical function.

Surface textures, which are generally thought to be detected with the human tactile senses can be represented partially with this device. Audible cues may be helpful in reinforcing the illusion of texture.

Chapter 5

Conclusion

5.1 Analysis

The haptic interface was constructed and software was written to create simple virtual environments. The device worked even better than expected; users reported having realistic force interactions with the virtual objects. Specifically, operators were able to discern objects of varying size, shape, and stiffness, by simply probing the virtual workspace with the device.

It appears that the device has the correct combination of the criteria outlined in chapter two. Of these criteria, the following seem most important:

1. The backdrive friction force of the device, 0.03 to 0.17 newtons, is not distracting to the human haptic system.

2. The maximum force that the device can exert, 9 newtons, is sufficient to give the illusion of immovable objects. When exploring the environment with a single finger, users rarely exerted more than 5 newtons of force.

3. Although most users did not agree with the statement that the virtual walls felt as if they were made of metal, most described them as "hard." The maximum

stiffness of this device was 32 newtons per centimeter.

4. Because cable reductions were used, the backlash for this device is zero.

5. The lightweight device has a very low rotational inertia about the axes and a low reflected inertia from the motors. Therefore, the apparent mass as felt by the user is very low (on the order of 70 grams for this device).

6. The device exhibits a high-bandwidth, and is therefore capable of accurately reflecting impact forces. The high bandwidth is a result of the low mass and high stiffness of the device.

Additionally, the simplification provided by using a passive three degree of freedom gimbal is crucial to this design. Specifically, the design requires only three actuated degrees of freedom to apply a force vector to the user's finger tip. Although it is not possible to apply torques to the user's finger, a high degree of functionality is maintained. The simplification of having all the torques equal zero and modeling the user's finger tip as a point in the virtual workspace also greatly simplifies the computation required for the virtual environment.

The human haptic system can be effectively coupled to the device using either the thimble or the tool handle interface. Each mode of coupling has its advantages for particular tasks. For example, some subjects claimed that they could detect finer detail when using the tool handle interface, while some subjects said that they felt more immersed in the virtual interactions when using their finger tip directly coupled through the thimble.

5.2 Applications

This device has an unlimited number of potential applications. It could function as a force-reflecting master to control the endpoint of a remotely located robot. The slave robot could be of an entirely different scale, allowing the user to conduct tasks like performing micro-surgery or constructing a space station.

The haptic interface could be coupled to a virtual environment and used in training systems. These training systems could allow doctors to practice surgery without any dire consequences. In fact, a version of this interface could enhance training in any situation where manual interaction is required.

The device could serve as a three dimensional force-reflecting mouse. In this implementation, the joystick would function as a general input/feedback device to/from the computer. This would provide a more natural way than keyboards and mice for users to interface to computers. In fact, a system such as this could give the blind better access to computers. Artists could use the device to paint on a virtual surface and the effects of the forces that an artist exerts upon the brush could be realized in the virtual drawing. The device could enable sculptors and engineers alike to interact with three dimensional models within the computer.

5.3 Improvements

Presently, the device can only be used for pushing, poking, scraping, and exploring with a single finger tip. If two of these devices were located side by side, one could be attached to the thumb while the other could be attached to a finger. This configuration would allow for a number of new haptic interactions. With opposing fingers, the user could grab, pinch, twist, and squeeze objects in the virtual environment. This improvement would take minimal effort, as it would simply involve constructing another identical haptic interface.

The true merits of this device will not be realized until the force-feedback it provides is combined with visual and audible feedback. Immediate work with this device should include interfacing it to a more powerful virtual environment with simultaneous force, visual, and audible cues. The bandwidth of this device, combined with the resolution of modern displays and the fidelity of available sound systems should provide a very realistic experience for users.

A closer evaluation of the relative importance design criteria might give insight into what parameters of this design can be changed to make the device even better. It will also be necessary to re-evaluate this design in terms of the criteria as new actuator technologies become available, because the motor performance presently limits the performance of the device.

This force-reflecting interface was designed so that tactile stimulators may be added at a later date. Tests should be conducted with this device to establish the importance of the tactile information in performing certain tasks. Preliminary results show that many tasks can be performed with the device as is.

Invariably, people will want to be able to measure rotations about and reflect torques to the finger tip. It may certainly be possible to measure the rotations of the axes of the passive gimbal with potentiometers, however torquing the gimbal with actuators located at the gimbal will severely degrade the performance of the rest of the system. The lost performance would be due to the added weight of the additional actuators. Although, the weight of the actuators could be statically balanced, the mass will increase the inertia and thus degrade the dynamic performance. Perhaps a better approach to achieving rotations about the tip of the finger would be to use two of the haptic interfaces connected to different ends of the same small bar.

Finally, the utility of this device could be greatly increased if the interface to the computer were improved. Specifically, it would be convenient if the device computed its own inverse kinematics and jacobian so that the host computer would not be so strained by these additional computations. Perhaps the haptic interface could use a dedicated micro-processor to perform these calculations. It may also be possible to do the jacobian and inverse kinematics in analog circuitry at a very high speed.

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