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Preliminary Tests of an Arm-Grounded Haptic Feedback Device in Telemanipulation

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Abstract

This paper investigates the use of arm-grounded force feedback applied to an operator's fingertips while performing telemanipulation tasks with a dexterous robot hand. The forces were applied by a cable-driven feedback device used in conjunction with an instrumented glove. Experiments were conducted to evaluate subjects' ability to discriminate between objects of different size and stiffness, and to regulate grasp forces. The results indicate that object size discrimination was comparable to using a conventional haptic feedback interface grounded to the environment, though still not as effective as direct human contact. The force regulation indicated that the user could maintain a fairly constant force, but was subject to some system noise. Discrimination of object stiffness was the most difficult task, due to the inherent compliances of the system and yielded a 75% success rate for distinguishing between compliant(150 N/m) and rigid objects.

Keywords: haptic, force feedback, telemanipulation

1. Introduction

Force feedback has long been recognized as an important capability for teleoperation of dexterous arms and hands. In previous work, fingertip force feedback has usually been accomplished with "desktop" devices (e.g. [3][4][12]), in which reaction forces are directed, or "grounded," through the base to a static reference frame (commonly a desktop or floor). These devices are capable of accurate fingertip force application but they have a limited workspace because they are mounted to a stationary platform. Devices that can apply forces to an operator's hand, while allowing free arm motions, have been much less common and, typically, quite bulky, such as the SARCOS dexterous master [11] and the SMU PHI [5].

Recently, the opportunity to provide high fidelity forces to the fingers of a person's hand using a portable system has appeared in the literature. Examples from academic labs include the Rutgers Master II [2] and the LPR Hand Master [17]. Another promising instantiation of this technology is the CyberGrasp™ haptic interface produced by Virtual Technologies[1], as an add-on to the instrumented CyberGlove®.

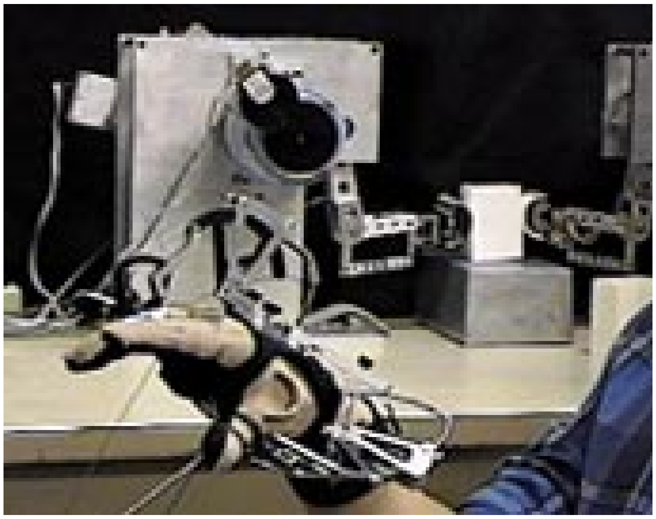

Figure 1: Teleoperation of a two fingered robot hand using an arm-grounded master.

Devices such as the CyberGrasp are examples of "portable hand masters." They can apply forces to the fingertips, but the reaction forces are applied locally to the user's hand or forearm, rather than a stationary platform. As a consequence, the realistic recreation of forces that are *internal* to the hand, such as grasp forces, is possible but the recreation of *external* forces, such as those that arise from contacting a surface in the environment, can give rise to unrealistic feedback. When the robot is touching a hard surface, the contact force at the fingertip is sensed by the user, and increases as the user continues to move into the surface. However, since this force is only grounded with respect to the user's arm, there is no physical impediment to further motion of the arm. This phenomenon has been remarked by several investigators including Srinivasan and Salisbury [12] and Gomez and Burdea [2].

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[1] Virtual Technologies, Inc.: www.virtex.com

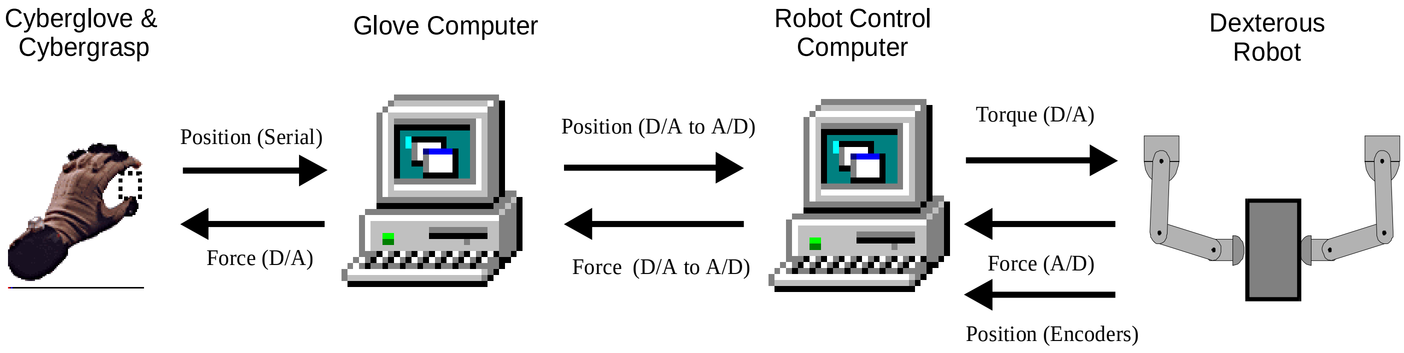

Figure 2: Connection Schematic

Richard et al. [10] have examined the effect of using ungrounded haptic interfaces while manipulating objects in a virtual environment. There has been little work done to quantify the performance of an ungrounded device in a telemanipulation environment.

Given the potential advantages in terms of reduced complexity, weight, and increased workspace of an ungrounded hand master as compared to a grounded system, we are interested in determining how well subjects can perform common tasks with an ungrounded system. In this paper we report on the results obtained while teleoperating a two-fingered dexterous robot with the CyberGrasp force feedback system. Subjects were asked to perform a series of object size and stiffness discrimination tests, and force-regulation tests. They commanded the robot motions through the instrumented glove and received force feedback through the cable-driven exoskeleton.

In the following sections we briefly review some of the literature that is particularly relevant to our work and then describe the experimental procedures and results.

2. Related work

There has been a significant amount of work in the field of force feedback for use in virtual reality or teleoperation. Massie and Salisbury [7], Rohling, Hollerbach et al [11] and Howe [3] have developed systems allowing a user to perform dexterous manipulation tasks using grounded interfaces. A good overview of the state of the art is contained in [1]. However, as mentioned earlier, there has been relatively little work on the efficacy of ungrounded feedback for teleoperation or interaction with virtual environments.

Tzatestas and Coiffet [17] describe an ungrounded, cable-driven hand master and control algorithms, used as part of a system for interaction with objects in a virtual environment.

Richard and Cutkosky [9] conducted a series of experiments using a single degree-of-freedom force-feedback apparatus that could be operated in grounded or ungrounded mode. They found that for such tasks as estimating the distance travelled to a contacting surface, ungrounded feedback was nearly as good as grounded feedback, with or without visual feedback. However, the distance of penetration into virtual surfaces was generally higher, and less repeatable, with ungrounded feedback.

It is important to know the limits of the human perception as a point of comparison to the tests in this investigation. Tan et al [14][15] tested the limits of human perception for differences in size, force and compliance. Srinivasan and Chen [13] examined a person's ability to apply stable static forces.

3. Experimental Setup

The CyberGlove and CyberGrasp system was connected to the CyberGrasp system controller running a real-time operating system with an update rate of 1000 Hz. The robot was controlled by a separate PC, again running at 1000 Hz. The position of the user's hand was measured by the CyberGlove, and that information was transmitted to the robot controller over two dedicated D/A channels and updated at 100 Hz. The robot controller provided readings from the force sensors on the robot to the CyberGrasp controller over two D/A channels at an update rate of 1000 Hz. Because of the high update rate, the forces displayed by the Cybergrasp were smooth (i.e. free of noticeable discontinuities or quantization).

The CyberGlove's individual joint sensors have a resolution of 0.5° and a repeatability of 1.0°. The CyberGrasp can apply up to 12 N to the tips of the user's fingers with a resolution of 0.01N and a bandwidth of 50 Hz. The robot used in the experiments is a two-fingered hand used for research in dextrous manipulation [6], event detection [16] and exploration [8]. Each finger has three degrees-of-freedom, each controlled by a dedicated DC servomotor. The workspace of the robot hand, for manipulation purposes, is approximately 100 x 100 mm, or slightly larger than the workspace of a human hand when manipulating small objects between the thumb and index finger.

The robot fingertip positions are measured with encoders, geared down to provide a position resolution of approximately 0.05 mm. At the end of each finger is a two axis force sensor with a sensitivity of approximately 0.1 N, and a hemi-cylindrical fingertip covered with a textured rubber "skin".

The robot is commanded by an impedance control law which drives the fingertips to a specified position. For the purposes of this experiment, the desired positions of each fingertip were controlled independently, taking position commands from the CyberGlove. The closed-loop servo rate is 1000 Hz, which enables smooth motion and force control.

Since the robot is a two-fingered manipulator, only two fingers of the glove/feedback apparatus were required. The middle finger and thumb were chosen, because they best approximate the kinematics of the planar robot manipulator. The force applied to the thumb and middle finger oppose each other directly while pinching, whereas the index and thumb forces, for example, are more skewed.

In order to test a simple pinch grasp, the motion of the robot was constrained to a horizontal line in the workplane. The commanded positions of the two robot fingers were based upon the positions of the tips of the operator’s middle finger and thumb. The system was recalibrated for each user so that the robot fingers were in contact when the user’s middle finger and thumb were in contact and fully spread when the user’s middle finger and thumb were fully spread. Since the robot fingers are symmetrical, while the human hand is not, the mapping from the middle finger to the robot is not identical to the thumb mapping. However, the difference is minor, and can be neglected when a consistent pinching motion is used.

4. Experiments

Twelve untrained operators were recruited for the experiments. Each operator’s right hand was fitted with a CyberGlove/CyberGrasp mechanism. A brief explanation of what the experiment entailed was provided, and each operator was allowed to practice grasping objects between the robot fingers to gain familiarity with the system. The operators were then asked to perform the object size discrimination test, followed by the force regulation test and finally the object stiffness discrimination test.

4.1 Object Size Discrimination

The object size discrimination test was used to examine how accurately the telemanipulation system conveys object size and contact occurrence. If the mechanism had too much compliance, or if it did not repeatably produce the force at the same position, objects of slightly different size would be indistinguishable.

For the object size test, the subjects were asked to discern which of two unseen objects was larger. One of two objects was placed between the fingertips of the manipulator for the subject to grasp, while the contact forces were relayed back. When the subject was ready, the second object was placed between the robot fingers. The subjects could ask for the objects to be exchanged as many times as they wished in order to help them in their decision.

Five different pairwise comparisons were used, and each was used twice. Each set was formed with a 75 mm block and one of five other blocks from 77.5 mm to 87.5 mm in increments of 2.5 cm. For example, a 17% difference was displayed using a 75 mm block and an 87.5 mm block. The size differentials were 3%, 7%, 10%, 13% and 17%. On the first run, the tests were given in increasing order of difficulty (i.e. 17% first and 3% last) to help the user develop a strategy. (Though whether the large block was shown first or last was randomized in each test, and the user was not told that the tests were getting more difficult.) On the second run, the difficulty order was randomized. No significant difference in the success rate was apparent between the two runs.

While the size difference in the robot’s grasp was fixed, the corresponding size difference in the user’s hands varied from subject to subject. This was primarily a function of the size of the users hand. However, since the robot fingers were calibrated to be in contact when the user’s fingers were in contact, the percentage difference in size was constant. In general, the perceived object size was smaller than the physical object.

As can be seen in figure 3, there was a 100% success rate in the 17% difference, tending to decrease with each size difference to a 75% success rate at the 3% difference. From a qualitative standpoint, the 3% test seemed to be near the limit of perception. Subjects tended to be significantly less confident and took longer to make a decision than in the higher value tests. No measurements of how long the subject took or how often they switched between objects were recorded.

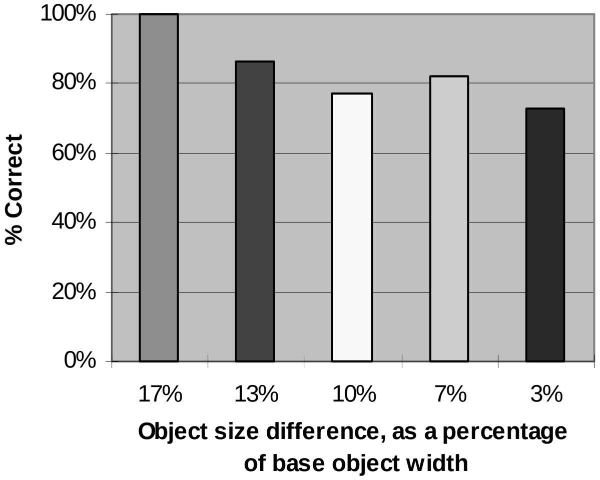

Figure 3: Object Size Discrimination Results

For comparison, Tan et. al [15] determined that the just-noticeable difference in the separation of the thumb and the index finger, when grasping parallel plates, is about 3% on average when the fingers are nominally 80 mm apart. Therefore, in our most challenging differentiation, it is possible that the users were limited by their own proprioception, in addition to whatever challenges the overall system may have provided. In an effort to separate these effects, users were asked to repeat the 3% test using their fingers directly on the object, and each performed the test successfully

The results obtained with CyberGrasp compare favorably to those reported by Richard and Cutkosky [9], where subjects were asked to compare wall positions simulated with a linear motor and requiring whole arm motions to move the finger. Their subjects had an 87% success rate for 5 mm (10%) differentials. The fact that the ungrounded apparatus appears to perform as well as a direct-drive linear motor, in this particular test, is an indication of good positional resolution.

In summary, the positional fidelity of the telemanipulation system seems to approach the limits of human proprioception when grasping objects. However due to the limited stiffness of the robot grasp, even a solid block will appear to have some compliance to the user.

4.2. Force Regulation

The force regulation test was used to determine how well a user can apply a consistent force using the telemanipulation setup. If the system cannot measure, apply and display forces in a consistent manner, it will not be possible to maintain a steady grasp force.

For the force regulation test, an acrylic block was placed within the workspace of the robot. A real-time measurement of the force applied to the object was displayed on the monitor of the robot controller. The user was asked to apply a constant force of approximately 2.5 N. The visual display was updated at a rate of 10 Hz. Each test was run for a minimum of 20 seconds.

The value of 2.5 N was selected as a representative force within the comfortable range of typical human pinch forces. The use of a single force level limits the generality of the conclusions that can be reached from this examination. Future efforts will include a spectrum of pinch forces for this test.

A typical example of the force results for a subject are shown by the solid line in figure 4. It is apparent that the setup is subject to some noise. Each user's results were subjected to the same apparent noise which has a frequency of about 3 Hz. The source of the noise is believed to be the A/D conversion of the commanded robot position signal on the robot controller.

The dashed line in figure 4 shows the results from performing the same test without any force feedback. The user could still use the force measurement on the monitor to regulate the commanded position of the robot, which allows control of the resulting force through the impedance control law.

In order to provide a point of comparison, the user's ability to apply a desired force directly to an object was tested. Figure 5 shows the results from a person applying force between the middle finger and thumb directly to one of the robot force sensors. To minimize variations between the two types of tests, the robot was commanded to maintain a static position, and the user was wearing the CyberGlove, though no positional input was recorded.

In order to eliminate any data from force ramp-up or ramp-down stages or possible distractions during the test, statistical analysis was performed on the user's most consistent five second span.

For the force feedback test, the best standard deviation was 0.06 N, with 0.10 N being the average. Subjects settled around values with 0.2 N of the target force. Without force feedback, their performance was not notably diminished. This is indicative of the coupling between force and position in the impedance control law. Force errors invariably produced significant (2 mm/N) position errors that became visible on the monitor. In the tests in which the user directly compressed the robot force sensor, their control of the magnitude of the force is greatly increased, settling to within 0.05 N and an average standard deviation of 0.05 N. In addition, the 3 Hz servo noise was greatly diminished.

In related experiments in which subjects pressed a force sensor while viewing a display on a monitor, Srinivasan and Chen [13] determined an average absolute error in force control of 0.04 N for a force of 1.5 N, with a standard deviation of 0.006 N. These results suggest that if the system noise can be reduced the force regulation ability of users in telemanipulation may approach the ability in direct manipulation, when visual feedback is present.

4.3 Object Stiffness Discrimination

The object stiffness test was used to test how smoothly the system ramps up forces. If the force ramp-up was irregular or discontinuous, it would not be possible to discern stiffness characteristics.

For the object stiffness test, the subject was asked to discern which of two objects of similar size was stiffer without looking. It was decided that this test was hindered more than the other tests by the kinematic mapping difference between the finger and the thumb discussed above. For this reason, the users controlled a single robot finger with their middle finger and compressed the object against a hard wall. Note that in this case, the lack of grounding is more significant because an internal grasp force is not applied.

Two objects of significantly different stiffness were used. One object was an acrylic block with a stiffness much greater than the commanded stiffness of the robot finger (set at 525 N/m). The second object was a block of soft packing foam with a spring constant of approximately 150 N/m, or 30% of the impedance of the robot control. The sizes of the two objects in an uncompressed state were equal, and both edges of the soft block were covered with a piece of acrylic to make the surface properties similar.

The subjects were fairly successful at determining which of the objects was stiffer, choosing correctly 75% of the time. However, many subjects described the process as the most difficult of the tests. Many said that while the two objects felt decidedly different, they were not always sure which one was stiffer.

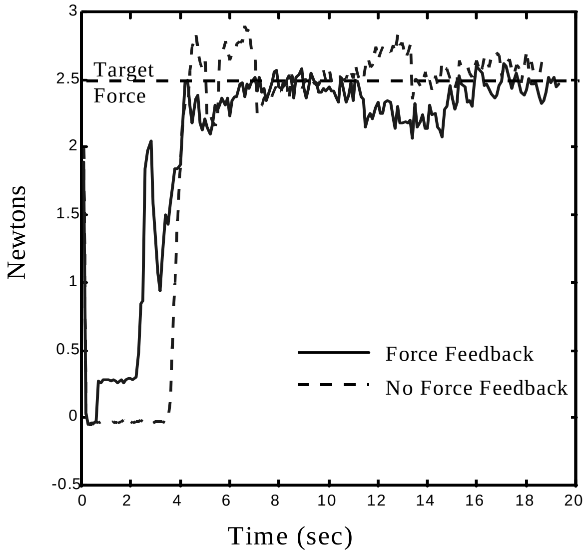

Figure 4: Typical Force Profile for Grasping Test

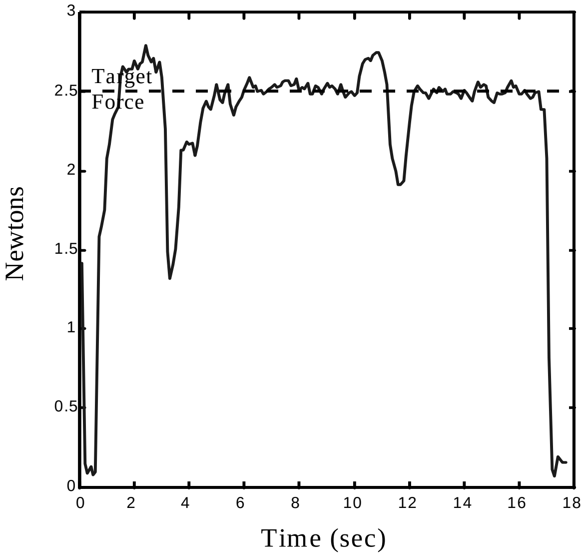

Figure 5: Typical Force Profile for Direct Force Test

There are two principal reasons why this test is more difficult than the size discrimination test. First, the impedance control of the robot makes it an inherently compliant system with an effective positional stiffness of 525 N/m. The user is essentially trying to tell whether there is an extra spring in series with the system. Second, the maximum force applied to the user's fingers was limited to 12 N to prevent injury. This level was low enough that users were able to move their fingers forward, even at maximum force.

That such a significant difference in stiffness is nearly undetectable shows the largest deficiency of the setup. For comparison, Tan and Srinivasan [14] found that when subjects pushed against an elastic beam with stiffnesses ranging from 15300N/m to 41500N/m, they could detect stiffness differences of 20%. It is likely that the current system can be improved by reducing system noise and friction. The performance in this test could also be improved by increasing the robot stiffness, at a cost to the force regulation ability, and by increasing the maximum force applied to the hand, at a cost of more user discomfort

5. Conclusion

It is clear from these tests that haptic feedback from a hand-mounted force-feedback system can provide useful grasping information during telemanipulation. We also observe that for the simple tasks we have explored, time lags, limited stiffness, and effects such as servo noise and friction are more serious drawbacks than the lack of grounded forces.

However, we should also acknowledge some difficulties. The results presented here represent a second set of experiments performed with the Cyberglove/Cybergrasp setup and the dexterous robot. In the original experiments (not discussed herein), the positional information between the glove computer and the robot control computer was sent over a serial line. In addition, the impedance control of the robot was optimized for smooth motions rather than minimized dynamic response. The result was a delay of 50 to 100 msec to position commands, which made the tasks more difficult and instabilities more likely.

In the first experiments, the users achieved comparable results in the object size test, but had significantly more difficulty in the force-regulation and object-stiffness tests.

It is clear that with the system described herein we are still not able to take full advantage of the proprioception and sensitivity of the human user with the current system. There are still physical lags in a telemanipulation system that do not allow one to display forces with the crispness and resolution that nature does.

Further experiments will focus on improving the communication bandwidth between the haptic interface and the robot controller and on improving the performance (i.e. stiffness and mechanical bandwidth) of the robotic manipulator.

6. Acknowledgments

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