Development and Testing of a Telemanipulation System with Arm and Hand Motion

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ABSTRACT

This paper describes the development of a system for dexterous telemanipulation and presents the results of tests involving simple manipulation tasks. The user wears an instrumented glove augmented with an arm-grounded haptic feedback apparatus. A linkage attached to the user’s wrist measures gross motions of the arm. The movements of the user are transferred to a two fingered dexterous robot hand mounted on the end of a 4-DOF industrial robot arm. Forces measured at the robot fingers can be transmitted back to the user via the haptic feedback apparatus. The results obtained in block-stacking and object-rolling experiments indicate that the addition of force feedback to the user did not improve the speed of task execution. In fact, in some cases the presence of incomplete force information is detrimental to performance speed compared to no force information. There are indications that the presence of force feedback did aid in task learning.

1.0 INTRODUCTION

We have developed a planar dexterous two-fingered robot hand which can be affixed to the end of a larger Adept® SCARA industrial robot as an end effector. This dextrous hand, called Dexter, can be seen in Fig. 1, and is controlled using the CyberGlove® device from Virtual Technologies. The industrial robot arm tracks the motions of the human arm as measured by a 6 DOF linkage attached to the user’s wrist. Movements of the human fingers are measured by the CyberGlove and Dexter is moved in a manner analogous to the user’s own movement. Forces measured by the robot hand can be displayed to the user through the cable-driven CyberGrasp haptic feedback mechanism. Incorporating the industrial robot substantially increases the user's workspace, allowing the hand to be continually positioned and oriented to best advantage. In addition, object motion is not restricted to a single plane.

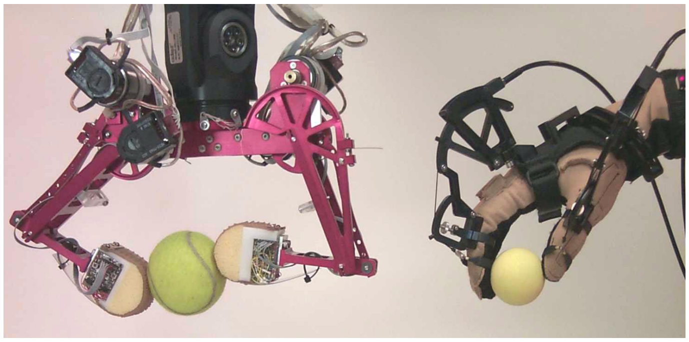


Figure 1. Dexterous robot with glove based interface

2.0 PREVIOUS WORK

Dexterous telemanipulation is an extension of the field of teleoperation. The goal of teleoperation is to allow a human to control a robot in a situation where it is inconvenient or unsafe to place a human and difficult to program a robot to perform autonomously. Some of these systems are operated by buttons and joysticks, while others are controlled by moving a kinematically similar master. The addition of force feedback in teleoperation tasks usually results in significant improvement in task completion time.[2][6][11]

We define dexterous telemanipulation as teleoperation where the end effector of the robot is a dexterous hand, and the robot finger motions are controlled by motions of the operators fingers.

Some of the previous efforts in this field were performed by placing the human hand in a mechanism which is a master version of the robot hand,[7][16] or by using an anthropomorphic robot hand.[8][13] The mapping from human to robot is simplified but requires a specialized input device in the one case and a complex and expensive robot hand in the other.

Some systems track the human hand through use of a vision system, which has the advantage of being non-intrusive at a penalty of cost and complexity.[10] Others, such as the glove used in this work, measure the finger motions directly.[3]

Haptic feedback, such as forces and vibrations, can be displayed to the operator through motors, cables or pneumatic actuators. An overview of haptic interfaces can be found in [1]. There are two principle types of force feedback: world-grounded, where the reaction forces are applied to an object external to the operator,[7] and arm-grounded, where the reaction forces are applied to the hand or arm of the operator.[4] The ability to display world grounded forces better reflects reality; research, however, has shown that in particular tasks arm grounded forces provide sufficient information to perform well, usually at a fraction of the cost and weight.[12][15]

This paper is a continuation of the work performed in [15], where the CyberGlove and CyberGrasp were used with a desk mounted dexterous robot to examine the perception limits of users in teleoperation.

3.0 HUMAN INTERFACE

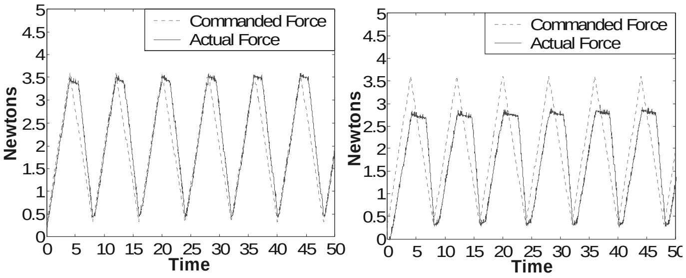
3.1 Instrumented Glove

Motions of the human fingers are measured by an instrumented glove. The CyberGlove, from Virtual Technologies, is a right handed glove with 22 bend sensors measuring most of the degrees of freedom of the human hand. The resolution on each sensor is 0.2° to 0.8° depending on the particular joint's range of motion. By reading only the appropriate sensors for the thumb and index finger, data collection can be run at 200 Hz. A predictive algorithm is used so the data appear to be continuous at 1000 Hz, and are used in robot control.

The glove was calibrated for each user by using a least squares regression to determine such parameters as finger length, sensor gains and sensor offsets. The resulting fingertip position accuracy was approximately 5 mm for manipulation of small objects. A more detailed explanation can be found in [5].

3.2 Arm-grounded Force Feedback

Force feedback is provided to the user's fingertips through the CyberGrasp mechanism, a cable driven device designed for use with the CyberGlove. A set of motors, worn in a backpack, apply tension to cables in teflon sheaths, which in turn apply forces to each finger. The forces applied to the finger are unipolar, since the cable can only pull along a single axis, and are grounded to the back of the user's hand, so no forces restrain arm motion.



Unflexed Cable

Flexed Cable

Figure 2. CyberGrasp force tracking with flexed and unflexed cable

The force applied to the finger acts to straighten the finger. The exact line of force action is configuration dependent, but in general has a positive projection onto the axis of pinch force between the index and thumb. For telemanipulation, the full magnitude of the pinch force is displayed to the finger, rather than a vector projection, to allow the user to regulate applied forces while manipulating an object. This results in somewhat inaccurate force direction information displayed to the user.

The motors can apply force up to 12 N and are updated at 1000 Hz to appear smooth and continuous to the user. The system has a resonance in the range of 20 Hz and a cutoff frequency on the order of 40 Hz. The principal performance constraint is static friction between the tendon and the sheath. Figure 2 shows that with an unflexed cable, the output forces track the commanded forces well, with some hysteresis when the tension is decreasing. If the cable is flexed the contact between the tendon and the sheath increases in area and force, and results in significant hysteresis for both increasing and decreasing cable tensions. The graph in figure 2 shows the friction property for a cable severely flexed (doubled back upon itself). During the tasks described below, the cables from the backpack to the user's hand are slightly flexed.

3.3 6-DOF Kinematic Linkage

The motion of the user's arm is measured by a six degree of freedom linkage attached to the back of the CyberGrasp on the user's hand. Each joint is measured with an encoder, measuring the hand position and orientation to within 0.5 mm and 0.2° respectively. The workspace of the linkage is approximately a curved horizontal cylinder 200 cm long with a cross sectional diameter of 30 cm. Roll, pitch and yaw motions all extend to ±90°, though there is a kinematic singularity when the pitch is ±90°. The device is counterweighted to ease the load on the user's arm, though extended use can grow tiring.

The device does not actively apply forces to the user's hand, but is a prototype for a world grounded force feedback addition to the CyberGrasp.

4.0 ROBOT SYSTEM

4.1 Dexterous Hand Design

"Dexter" is a two-fingered robotic hand, with two degrees of freedom per finger. Each degree of freedom is powered by a low friction, low inertia DC servomotor. The motor is connected to the link through a cable/drum drive similar to those found in haptic feedback devices such as the PHANToM® by Sensable Devices. As a result, the hand has very low friction and is backdrivable. The motors are fairly small, due to weight and space limitations, but are still capable of providing enough force at the fingertips to pick up a 250g object, such as a softball, which more than suffices for the purpose of these experiments.

The links are 100 mm long, and each has over 120° of motion. The workspace of the hand is about 400 mm by 150 mm, with a positional resolution of 0.08 mm. This workspace is sized to best manipulate objects from about one to three inches in diameter. Manipulation is not limited to spherical objects; the telemanipulation tasks (discussed later) involve manipulation of square blocks and cylindrical objects.

Two-axis strain gage force sensors have been incorporated into the robot fingertips to read the forces applied by the robot to the object. The force sensors have good linearity and are accurate to ± 0.1 N up to 5 N. The fingertips have a foam core and a compliant, textured rubber skin in order to minimize contact instability and decrease object slipping.

4.2 Software Control of Dexterous Hand

Dexterous manipulation requires continuous and accurate control of finger forces and positions. The physical properties of the system were determined empirically, and a software control system was established.

The robot fingers are controlled by a proportional and derivative control law about a desired position, with feed forward compensation for gravity and system inertia. By utilizing an operational space framework [9], the equations of motion for a single robot finger can be modeled as:

$$\Lambda(\boldsymbol{x})\ddot{\boldsymbol{x}} + \mu(\boldsymbol{x}, \dot{\boldsymbol{x}}) + p(\boldsymbol{x}) = F \tag{1}$$

Where $\Lambda(\boldsymbol{x})$ represents the configuration dependent mass matrix of the system, $\mu(\boldsymbol{x}, \dot{\boldsymbol{x}})$ represents the Coriolis and centrifugal forces, $p(\boldsymbol{x})$ represents the gravity force, and F represents the operational space force vector.

Dynamic decoupling and motion control of the robot in operational space can be achieved using the following control structure:

$$F = \hat{\Lambda}(\boldsymbol{x})F^* + \hat{\mu}(\boldsymbol{x}, \dot{\boldsymbol{x}}) + \hat{p}(\boldsymbol{x}) \tag{2}$$

where $\hat{\Lambda}(\boldsymbol{x})$, $\hat{\mu}(\boldsymbol{x}, \dot{\boldsymbol{x}})$, and $\hat{p}(\boldsymbol{x})$ represent estimates for $\Lambda(\boldsymbol{x})$,$\mu(\boldsymbol{x}, \dot{\boldsymbol{x}})$, and $\mathrm{p}(\boldsymbol{x})$, respectively. The operational space mass matrix $\Lambda(\boldsymbol{x})$ is derived from the empirically calculated joint space mass matrix and the Jacobian at each time step. Because the finger is moving relatively slowly during a manipulation, the $\hat{\mu}(\boldsymbol{x}, \dot{\boldsymbol{x}})$ term is assumed to be negligible. With perfect estimates the end effector becomes equivalent to a simple unit mass system,

$$\ddot{\boldsymbol{x}} = F^* \tag{3}$$

where F^* is the input to the decoupled system.

The operational space formulation and smoothed continuous commanded position updates allows us to implement a PD control law with gains computed for the desired response as if the robot was a unit mass system. In this way we can smoothly and stably control the motion of the robot fingertips in cartesian space, with a desired stiffness and damping. The control law is as follows:

$$F^* = -K_p'(\boldsymbol{x} - \boldsymbol{x}_{\mathrm{des}}) - K_v'(\dot{\boldsymbol{x}} - \dot{\boldsymbol{x}}_{\mathrm{des}}) \tag{4}$$

From F in equation 2, we calculate the necessary joint torques T using

$$T = J^T F = J^T(\hat{\Lambda} F^* + \hat{p}(\boldsymbol{x})) \tag{5}$$

where J is the robot finger Jacobian.

4.3 Industrial Robot Arm

The robot hand is placed on the end of an Adept 1, a 4 DOF SCARA industrial robot arm. The Adept has a positional resolution of 0.04 mm and 0.05° in the rotational axis. The workspace is approximately 1100 mm long by 350 mm wide by 175 mm high. The robot trajectory is controlled by the Adept controller, which requests new commanded positions as needed.

The speed of the Adept robot is limited for the safety of the robot hand. The speed limitation and the lack of direct control of the robot motors results in a noticeable lag between human arm motions and robot arm motions.

5.0 COMMUNICATION

Communication lag between the controller and the actuator can lead to instabilities, particularly in a force control system. To avoid this problem, almost all of the computations are performed on a single computer.

The principle controller is a Pentium 233 MHz machine running the QNX real time operating system. Using a real time OS allows us to run multiple processes simultaneously at different rates and different priorities, with near instantaneous communication between processes. For example, robot motor torques are updated at 1000 Hz with high priority even though the hand kinematics (mass matrix, Jacobian) are updated at 200 Hz and the graphic interface is updated at 7 Hz. The various processes effectively run in parallel rather than in series.

The CyberGlove is connected to the controller through the PC's serial port. The CyberGrasp is controlled by a Servo2Go card connected to the motor amps. The dexterous robot hand is controlled by a separate Servo2Go card connected to linear current motor amps which also reads the encoder values and force sensors. The kinematic linkage has a separate controller which communicates the joint angles with the main computer over a digital I/O.

The Adept robot controller generates a smooth and stable trajectory for the Adept robot. The Adept controller requests and receives new positions over an ethernet connection from the principal controller whenever the trajectory path can be amended. The lag between the human arm motions and the Adept arm motions is not a function of the communication, but is due to the speed constraints on the Adept which means it will not reach the latest position for a finite amount of time. This lag could lead to accidental collisions between the end-effector robot and the world, but users seemed to quickly adjust.

6.0 TESTING

A diverse set of ten subjects were asked to perform two prototypical manipulation tasks in order to evaluate the performance of the system. Each subject had the CyberGlove calibrated to their hand, and the mapping to the robot hand customized to best allow the robot fingers to follow the motions of the subject's fingers.[5]

Subjects performed each task twelve times, six with force feedback from the CyberGrasp and six without it in a pattern of AAAA-BBBB-AA-BB, where A is one force mode (on/off) and B is the other. The pattern was selected in an effort to minimize the effect of learning. Each subject has a trial with each force mode near the end of the task set, and time to completion analysis was performed on each subject's best run under each condition. In order to eliminate order-sensitive issues, a random determination was used to select whether a subject began with force feedback on or off.

The time to completion of each trial was measured, as well as the subject's success in completing the task.

6.1 Block Stacking

The subjects were asked to construct a tower of four blocks upon a target location, as seen in Fig. 3. This test examines whether the presence of the internal forces displayed by CyberGrasp affects performance of a primarily pick-and-place task.

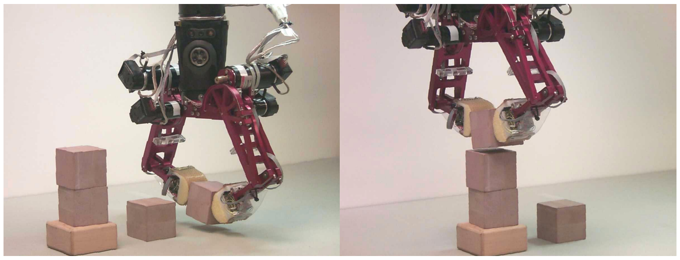


Figure 3. Block Stacking

The task began with the four 50 mm blocks in preset locations and the robot hand and arm in the designated "safe" area. The time measurement started when the robot arm left the safe area. The subject controlled the robot arm to guide the robot hand over the block and then grasped the block. The block is carried to the target spot and placed. The grasp and place motion was repeated on three more blocks to construct the tower. In order to place the final block on the tower, it was usually necessary to move the block upward within Dexter's workspace.

If a subject dropped a block within the workspace of the robot, they could pick it back up and continue. If the subject knocked over the tower or dropped a block beyond the workspace of the robot the task was considered unsuccessful.

The quantitative results do not show a significant difference in time to completion or number of failures. Figure 4a shows the ratio of time to completion without force feedback to the time to completion with force feedback of each subjects best run for each condition. The average time ratio for subjects was 1.03, meaning that the best run with force feedback was typically only 3% faster than the best run without force feedback. Similarly, Fig. 4b shows that the total number of unsuccessful trials was nearly identical for the two conditions.

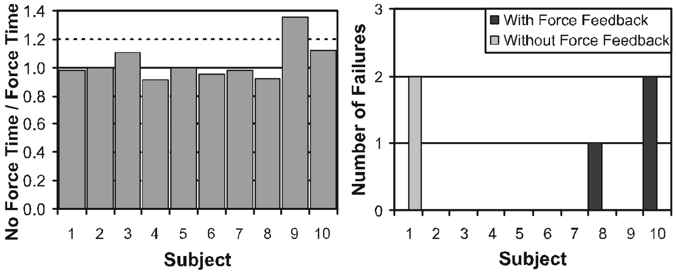


Figure 4. Completion time ratio and failure occurrences for block stacking

Qualitatively, most of the subjects preferred the force feedback mode. During the run, comments such as "That feels nice," and "The forces tell you where you are and what is going on," were common. Upon completion of all the tasks, all subjects said they felt more comfortable with the forces on in this task. Some subjects pointed out that the forces could still mislead you, however. One subject mentioned that touching the table felt exactly the same as touching the object, since the

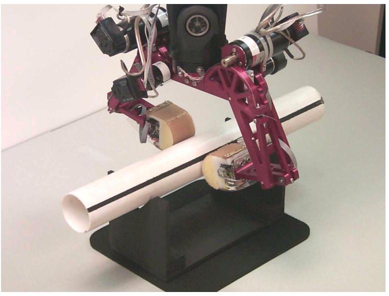


Figure 5. Knob Turning

CyberGrasp can only pull in one direction.

One interesting subject comment is that it seemed easier to learn the task with force feedback, but once a subject was comfortable it didn't seem to make much difference. The data collected seem to support this. Subjects who started the task with force feedback on performed noticeably faster (on average, 15%) on their first trial than those that did not have forces on their first trial. Unfortunately, due to the small subject pool we can not make this statement with any statistical confidence.

A likely reason for the overall lack of time difference between the two modes, besides human muscle memory and proprioception, is that a significant portion of the task involved moving the larger and slower industrial robot arm. Conditions for moving the arm were identical in the two force modes and likely contributed significantly to the overall time.

6.2 Knob Turning

The subjects were asked to use the robot fingers to roll a cylinder through a full 360° rotation, as seen in Fig. 5. The purpose of this task was to examine the effect of the CyberGrasp force feedback on performing two fingered manipulation.

The task began with the 400 mm long by 50 mm diameter cylinder resting in two V-shaped notched supports near the ends of the cylinder. The robot hand was located above the cylinder. The subject was instructed to lower the hand and rotate the object through a full clockwise rotation. If the subject knocked the cylinder off of the stand, the attempt was considered to be unsuccessful.

No instructions were given to the subjects about the method of rotating. Most subjects did primarily use two fingered manipulation, though some subjects rotated the cylinder by pushing it with a single finger.

The subject-to-subject variability was high in this task, probably due to varying levels of mapping quality from the human to the robot. One subject rotated the object with nearly flawless two fingered manipulation on his first attempt, with a time lower than many subjects' best performance. Other subjects struggled to coordinate their finger motions even after several trials.

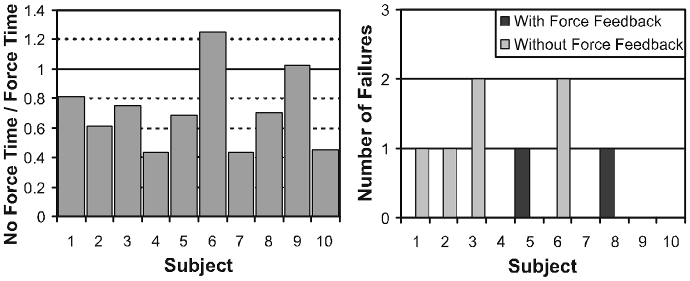


Figure 6. Completion time ratio and failure occurrences for knob turning

It was fairly clear from watching the subjects that the addition of force feedback actually impeded their ability to roll the object quickly. Figure 6a shows the ratio of best run without force feedback over best run with force feedback for each subject. The average ratio across subjects was 0.72 (a ratio of 1.0 would indicate no difference in performance due to force feedback, while a ratio less than one indicates faster completion time without force feedback). Thus, on average, the subjects' best run without force feedback was 28% faster than their best run with force feedback. Using a bootstrap t-test to resample our data, we can state with 95% confidence that the mean population ratio would be 0.72±0.16, illustrating that force feedback has a negative effect on subject performance with respect to this task.

Conversely, Fig. 6b displays that our subjects were three times more likely to have a trial failure without force feedback as compared to with force feedback (a 10% failure rate compared to a 3.3% failure rate). Analyzing the data with a bootstrap t-test to examine whether the population is more likely to have a failure without force feedback, we get an α value of 20%. This is not significant enough to state strongly, but it is a promising indication and should be examined further.

These results are confirmed by the qualitative comments made by the subjects. One subject pointed out that the system does not provide a sensation of curvature or rolling. Another subject said, "The forces don't match what I see, so I don't know how to adjust my hand". The difficulty of the task may be due in part to the uncommon motion. One subject pointed out that she really wanted to grasp the cylinder and turn it with her wrist.

Despite the fact that overall performance was better without force feedback, we continue to see indications that it was easier to learn how to perform the task with force feedback than without. Subjects who started the task with force feedback on performed noticeably faster (on average, 17%) on their first trial than those that did not have forces on their first trial. Unfortunately, due to the small subject pool we can not make this statement with any statistical confidence.

These results indicate that the single axis of force representation provided by the CyberGrasp does not sufficiently represent the expected forces for rolling an object, and the potentially misleading information slows the user more than having no force information. Rolling of an object uses regulation of the ratio of normal to tangential forces, which cannot be displayed by this system. However, the presence of contact force information does seem to improve a user's ability to maintain a stable grasp and aid the task learning process.

6.3 Results

The results indicate that the CyberGrasp force feedback system does not increase speed of performance for simple telemanipulation tasks such as block stacking and object turning. This is due in part to human skills in learning and muscle memory, as well as the imperfect force transparency due to the single degree of actuation.

Conversely, there is some evidence that force feedback improves manipulation stability and may benefit the task learning process. Subject responses indicate that force feedback's benefits may be more apparent in tasks which require delicacy or precision. One pointed out "It seemed a little more difficult with the forces, because you are taking care where your fingers are.... Otherwise, you just pinch as hard as possible." and another said, "Without forces you aren't worried about damaging the machine or forcing things".

For the future, we would like to further investigate the hypotheses that the force feedback is more beneficial to controlling stability in manipulation and that it accelerates the task learning process.

Some improvements need to still be made in our testing platform. The speed of the large industrial robot arm can be improved to eliminate undesirable lags and vibrations. Customizing the mapping process for each person can be improved by automating the process and/or developing a measure of mapping quality. We are also investigating a more object centered mapping process, which should increase transparency.

7.0 ACKNOWLEDGMENTS

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