IEEE International Conference on Robotics and Automation, (ICRA '04)
New Orleans, USA, April 26 - May 1, 2004, pp. 4147-4152.

Design and Operation of a Force-Reflecting Magnetic Levitation Coarse-Fine Teleoperation System

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***Abstract*— This paper describes the design and operation of a coarse-fine teleoperation system with bilateral force reflection. The system uses a 6-DOF magnetic levitation device (MLD) master to control a 6-DOF fine-positioning MLD slave mounted on a 6-DOF coarse positioner arm. Coarse-fine teleoperation expands the workspace of the slave MLD while retaining its frictionless characteristics, fine position resolution and high bandwidth. Several modes of operation are explored. In unilateral coarse-fine mode (UCF) the master controls the wrist position which in turn controls the coarse positioner. In master deadband rate control mode (MDRC) the master position controls the coarse positioner velocity while wrist position is used to reflect contact forces to the master. In symmetric bilateral control (SBC) mode the wrist and master servo to each other's positions providing force reflection during fine manipulation. Operation of each system mode is investigated during a simple assembly task.**

I. Introduction

Teleoperation systems enable persons to interact with environments at a distance, allowing the performance of dangerous or difficult tasks. They also provide a means for scaling human forces and motions up or down to levels not achievable without mechanical assistance.

While information flows from the user to the environment through the teleoperation system, information flow from the environment to the user is also important. Visualization of the workspace is vital and force reflection has been shown to reduce task performance time and excessive force levels when added to a teleoperation system [1].

An ideal teleoperation system should be able to operate over a large workspace with fine position resolution and also supply realistic haptic feedback to the user. Unfortunately, these qualities are difficult to find in a single device. Previous studies have shown that magnetic levitation devices (MLD's) provide backdriveability, zero static friction and high position and force bandwidths [2]. They have been used previously in the design of systems similar to the one described in this paper [2], [3]. In these systems, master and slave MLD's were identical and the slave was carried on a conventional manipulator arm. By attaching a fine motion slave MLD to a coarse motion conventional arm it is possible to take advantage of the superior position resolution, low friction and high bandwidth of the MLD while gaining the large workspace of the arm.

The control of such a 12-DOF coarse-fine slave by a single 6-DOF master presents an interesting challenge. Generally, the coarse slave arm will have much poorer position resolution and much lower bandwidths than the fine slave MLD. Subsequently, the dynamic characteristics of the MLD carrier arm may have significant deleterious effects on desired system behavior [4]. However, by the use of rate control, indexing, and variable compliance it is possible to effectively retain the desired characteristics of the slave MLD.

In this paper we demonstrate a force-reflecting teleoperation system designed using two MLDs of differing design and a conventional 6-DOF manipulator. The system was designed for psychophysical studies of system transparency [5]. We describe several modes of operation along with preliminary performance results. Finally, whereas previous studies have looked at device characteristics [2], [3], [6], we will present results obtained for a simple teleoperated assembly task.

II. System Components and Design

A. Overview

The telemanipulation system is made up of three distinct devices: a master, a slave wrist, and a slave coarse motion device. The master and slave wrist use Lorentz levitation to

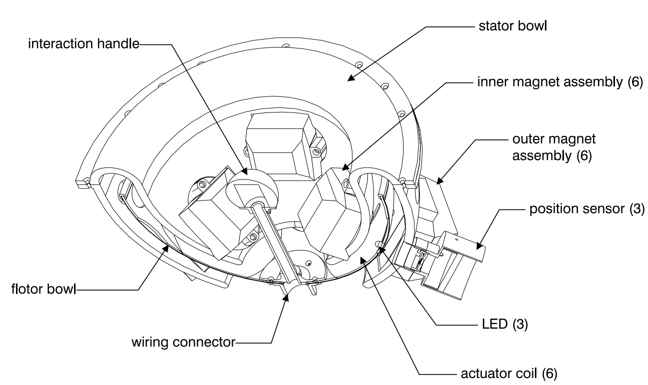

Fig. 1. Lorentz magnetic levitation master cut-away view of design.

provide high position and force bandwidths and to eliminate static friction [2]. Both wrist and master are capable of 6-DOF motion. Since the wrist has a limited range of motion, it is carried on a 6-DOF PUMA 560 robot arm, effectively extending its workspace to that of the PUMA's. The resulting system has a 6-DOF master driving a 12-DOF coarse-fine slave.

B. Telemanipulation Master

The master device is responsible for commanding slave position and/or rate and for providing force feedback from the slave's environment to the user. Ideally, the master should have high position and force bandwidths, fine position resolution and a wide range of impedance. Six DOFs are necessary to emulate the forces and torques encountered in realistic 3D assembly tasks. The magnetic levitation master device used in this system, shown in Fig. 1, provides such a platform [7].

The magnetically levitated part of the device, the flotor, has six coils embedded in a hemispheric aluminum shell enclosed within fixed magnet assemblies. Current in each coil interacts with the magnetic fields of the enclosing magnets to produce an arbitrary force/torque wrench on the flotor, and thence to an attached manipulandum and the operator's hand. Three LEDs on the flotor are sensed by fixed optical sensors and provide position resolutions of 5-10 μm depending on location in the workspace. Because of the low flotor mass and freedom from static friction, high position bandwidth ($\sim$125 Hz at $\pm$3 dB) is achieved [8]. Maximum stiffness is approximately 25 N/mm in translation and 50.0 Nm/rad in rotation [8]. 6-DOF motion of the handle has a range of $\pm$12 mm in translation and $\pm 7°$ rotation in all directions. The master has a PD controller that runs at 1 KHz on a dedicated processor. Gains have been optimized for maximum stability and performance.

C. Telemanipulation Slave Device

The telemanipulation slave device in our system is shown in Fig. 2. The IBM Magic Wrist is a 6-DOF fine motion device that can be attached to the last link of a conventional robot to give the robot extraordinary compliant motion and positioning

Fig. 2. Magic Wrist slave device.

Fig. 3. Coarse-fine slave.

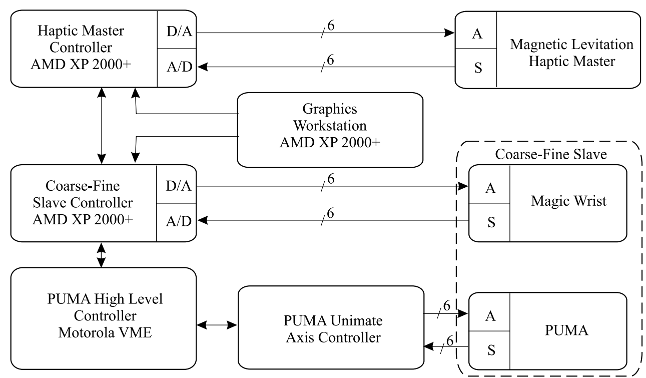

Fig. 4. Coarse-fine telemanipulation system components and information flow.

capabilities. In our system, the wrist is attached to the tooling mount of the PUMA 560 industrial robot (Fig. 3).

The slave's flotor is levitated by six Lorentz actuators arranged at $60°$ intervals around a horizontal ring. Each actuator has a line of action at $45°$ with respect to the vertical axis of symmetry. The wrist's fixed stators are attached to the distal link of the PUMA 560 arm, whereas the coils of each actuator are contained in the thin, hexagonal flotor shell. The position of the flotor with respect to the stator is sensed by optical beams projecting from the stator to position-sensing photodiodes attached to the inside of the flotor. The flotor has a motion range of ± 5 mm in translation and $\pm 4°$ in rotation, a position resolution of approximately 1 μm, and a position bandwidth of about 40 Hz [6]. It has a 1 KHz PD controller running on a separate processor. Gains have been optimized for maximum stability and performance. A small, pneumatically-activated gripper mounted on the wrist provides an end effector.

The coarse positioning robot is controlled by a Motorola VME 162-23 computer running RCCL/RCI software [9]. The controller communicates with the PUMA via its Unimate controller. Wrist and PUMA motions are synchronized by a high level manager running on the same processor as the wrist controller. The manager communicates with the PUMA at approximately 60 Hz.

A graphics workstation, the master and the coarse-fine slave are interconnected via Ethernet, providing a central point for user control of the various system components. Fig. 4 shows a block diagram of their interconnections. Two channels are available for interprocessor communication: a reliable command channel which operates at 100 Hz and a high speed data channel which operates at 1 KHz. Workstation commands to the master and slave use the former, while master and slave exchange position/orientation information using the latter.

During a teleoperated assembly task a video camera provides realtime visualization of the field of operation. Video data is transmitted over IEEE 1394 Firewire and displayed using open source Coriander[1] software.

III. Modes of Operation

Our system has been operated and tested in several different modes. Depending on the mode, the position of the master or of the slave may be used to provide rate control of the PUMA. The master's position may also be used to control the position of the slave wrist and, in modes providing force reflection, the position of the slave wrist provides position control of the master.

A. Unilateral Fine Teleoperation

The simplest mode of operation is one in which the slave wrist servos to a scaled-down master device position. The coarse positioner does not move. This mode does not provide force reflection to the user and allows motion only within the wrist's limited workspace. It provides a way of testing the fidelity of the system's fine movement capabilities.

A 1 Hz square wave was used to drive the master along each axis and the position of the wrist and master were recorded at 50 Hz. As can be seen in Fig. 5, the *x* and *y* axis appear more underdamped than the *z* axis. Underdamping may be due to the gripper which is symmetrical about the *z* axis but alters the center of mass from the center of forces along the other axes.

Both the wrist and master have position resolutions on the order of micrometers. Micromanipulation is therefore possible using a suitably scaled-down master position to drive the wrist. A 0.5 Hz square wave input of 20 μm amplitude was used to drive the master. The wrist position was servoed to one third of the master position. As can be seen in Fig. 6, the subsequent movement of the wrist accurately follows the master. The small fluctuations in master and slave are likely due to noise in the master and wrist position sensors.

During unilateral fine teleoperation, the forces required to servo the wrist to the master's position were measured. As seen in Fig. 7, a large transient force is exerted on the master at the start of the square wave, while a much smaller force drives

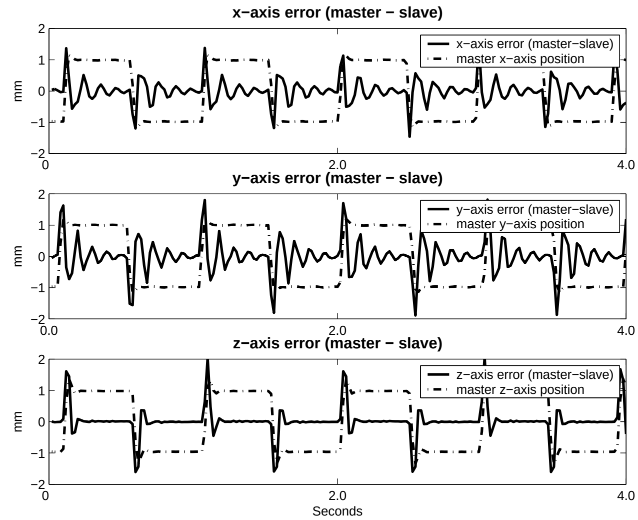

Fig. 5. Error in wrist position during square wave input to master (scaled with offsets removed). Position of the master is shown for reference.

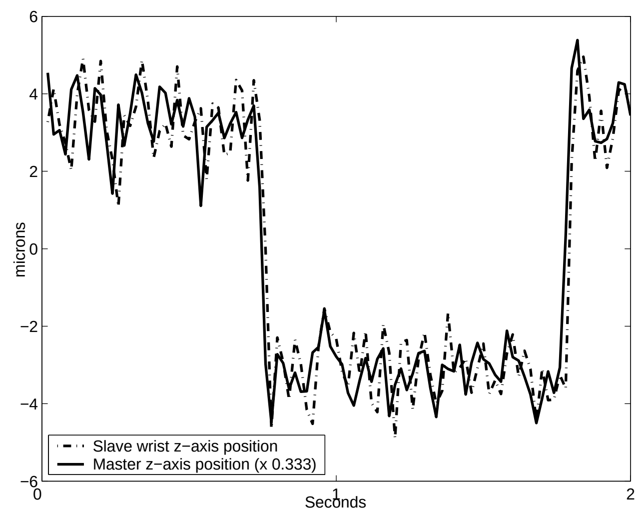

Fig. 6. The slave wrist tracks a very small amplitude square wave input from the master in the *z* axis. The master's unscaled wave amplitude is 20 μm at 0.5 Hz while the slave's is approximately 7 μm. The scaled master position ($\times$0.333) is shown for reference.

the lighter wrist. The wrist force shows more underdamping than the master since its gain settings leave it more compliant than the master.

B. Unilateral Coarse-Fine Teleoperation (UCF)

It is possible to extend the limited workspace of the wrist without sacrificing its position resolution. By having the PUMA track the center of the wrist's workspace, the wrist can be moved to any position X_{sd} within the PUMA's considerable workspace [3]. Small motions of the wrist flotor, within a distance r_w from its workspace center result in no motion of the PUMA. However, once the wrist moves outside of this spherical deadband, the PUMA is activated (see Fig. 8). The PUMA is rate controlled until the wrist moves back within

[1] http://www.tele.ucl.ac.be/PEOPLE/DOUXCHAMPS/ieee1394/coriander

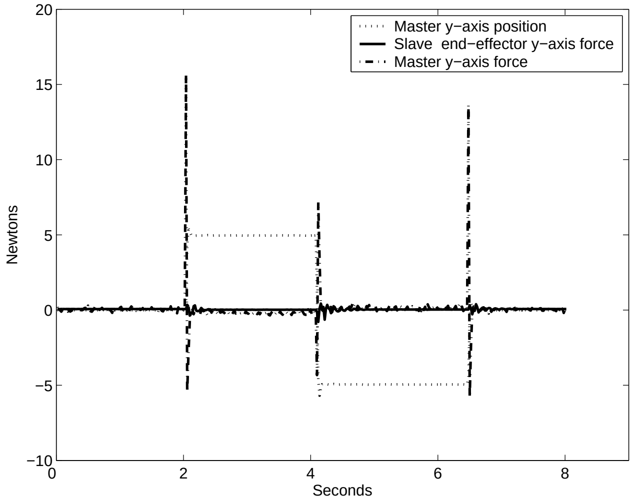

Fig. 7. *Y*-axis forces generated by the master and slave wrist during 1 Hz square wave input. The master *y*-axis position is shown for reference.

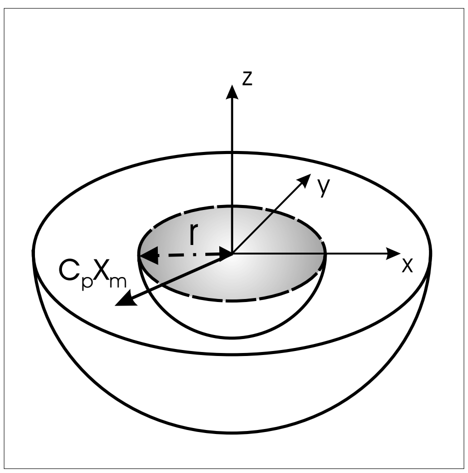

Fig. 8. Cross-section of magnetic levitation device workspace and deadband.

the deadband. The position of the wrist flotor with respect to its workspace center is based on a scaling factor c_p and the master position x_m. While the wrist is outside the deadband, a scaling function $f(\|c_p x_m\|)$ determines the PUMA's velocity, $\dot{P}$. The master can thus be used to move the wrist and PUMA simultaneously:

$$X_{sd} = c_p x_m + P, \tag{1}$$

$$\dot{P} = \begin{cases} f(\|c_p x_m\|) & \text{if } \|c_p x_m\| > r_w; \\ 0 & \text{if } \|c_p x_m\| \le r_w. \end{cases} \tag{2}$$

A deadband of diameter 0.5 mm was implemented on our system. Fig. 9 shows the resulting behavior. A small wrist displacement outside of the deadband results in a large PUMA motion, while, inside the deadband, motion resolution remains on the order of micrometers.

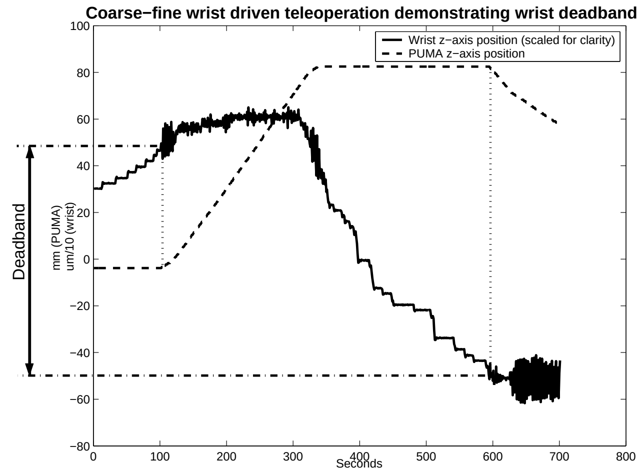

Fig. 9. Coarse-fine teleoperation with 0.5 mm diameter wrist deadband.

C. Master Deadband Rate Control (MDRC)

A small deadband of radius r_p can be placed about the center of the master's workspace instead of the slave wrist's. The PUMA is then controlled by the master's position in the master workspace. While the master flotor remains outside its deadband, the PUMA moves under rate control. The wrist does not move from the center of its workspace:

$$X_{sd} = P, \tag{3}$$

$$\dot{P} = \begin{cases} f(\|x_m\|) & \text{if } \|x_m\| > r_p; \\ 0 & \text{if } \|x_m\| \le r_p. \end{cases} \tag{4}$$

The deadband allows the user to stop PUMA motion. If it were not present, the user would need to position the master exactly at its center point to hold the PUMA steady. The motion of the PUMA has no effect on the master, therefore, for safety purposes, a small centering force is applied to the flotor. This force brings the master back into the deadband, stopping PUMA motion if the user accidentally releases the master's manipulandum.

The centered slave wrist has a compliance dependent on its gain settings. It can still be moved by contact forces. If its position is used to control the master's position, it functions as a variable compliance force-torque sensor and provides force reflection to the user. Because of the fine position resolution of both MLD's, the user can feel small surface details encountered by the wrist while being restricted to coarse motion with the PUMA.

D. Coarse-Fine Teleoperation with Symmetric Bilateral Control (SBC)

Unilateral coarse-fine control can be extended to provide the user with the ability to *feel* objects and surfaces with the master, while they are being manipulated by the slave. Symmetric bilateral force reflection between master and slave is implemented by passing position/orientation information between their respective servo loops. Each MLD then servos

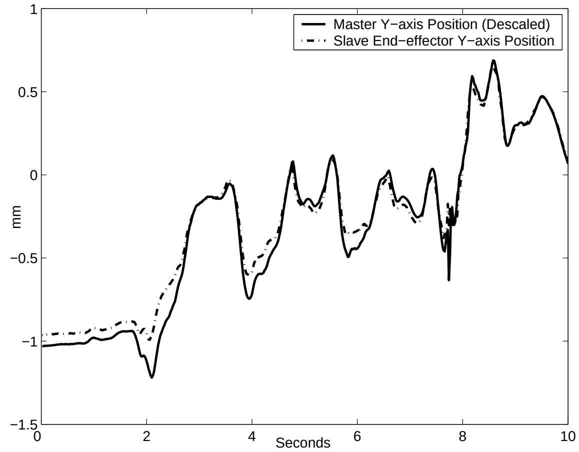

Fig. 10. Master and wrist y-axis position during a SBC task.

to the other's position (see Fig. 10). In our system, the user switches between UCF and SBC mode by indexing, but it is possible to use both modes at once.

IV. Assembly Task Results

To test the functionality of our system in a real world environment, an assembly task was performed using UCF, MDRC, and SBC modes . A pneumatically-driven gripper, attached to the slave wrist, grasps a 4×4 Lego^{TM} block. The user moves the 4×4 block into position above another block, orients the block correctly and snaps it into place (see Fig. 11).

During UCF mode operation, there is no force reflection and the user must rely on vision to perform the task. Both MDRC and SBC modes provide force reflection, however MDRC permits only coarse motion while SBC mode allows both coarse and fine motions. Users should therefore find the task harder in UCF and MDRC than in SBC mode. Greater task difficulty may result in longer completion times. Larger forces may be applied when no force reflection is available.

While formal analysis with naive users has yet to be performed, our experience with the system appears to confirm these hypotheses. Representative z-axis position and force data can be seen in Figs. 12, 13 and 14.

Referring to Figs. 12, 13 and 14, the z-axis force in all three modes remains fairly constant, counteracting gravity, prior to contact between block and surface. Figure 12 shows results from the UCF task during the final stage of assembly. The PUMA arm approaches the surface (A) and the block makes contact (B). Several large force oscillations occur prior to the block snapping into place (C) since the user is working with only visual feedback.

During the MDRC task (Fig. 13), the user contacts the surface (A) vigorously and large oscillations in force occur. The lack of fine position control prevents the user from making gentle contact and once attached (B) the block is pulled up again as the user struggles with the coarse control of the PUMA. It should be noted that in both UCF and MDRC modes multiple attempts were required to accomplish the task.

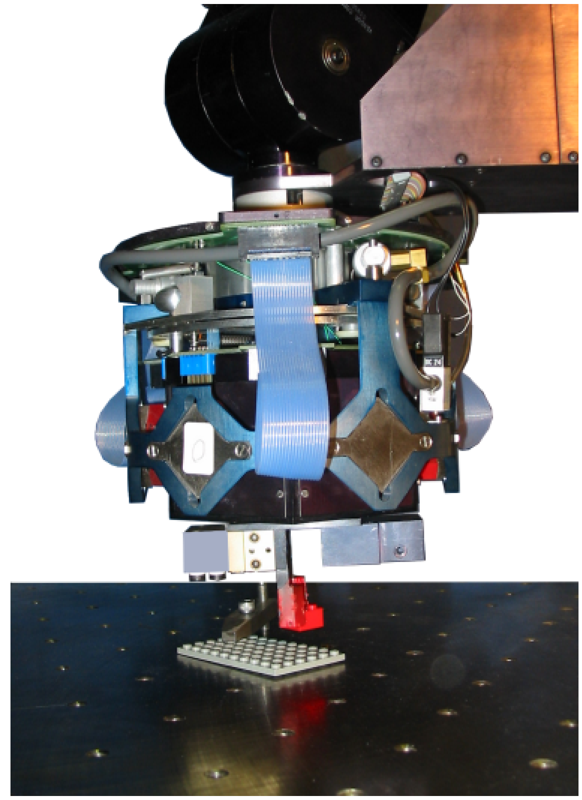

Fig. 11. Wrist and gripper during block placement task.

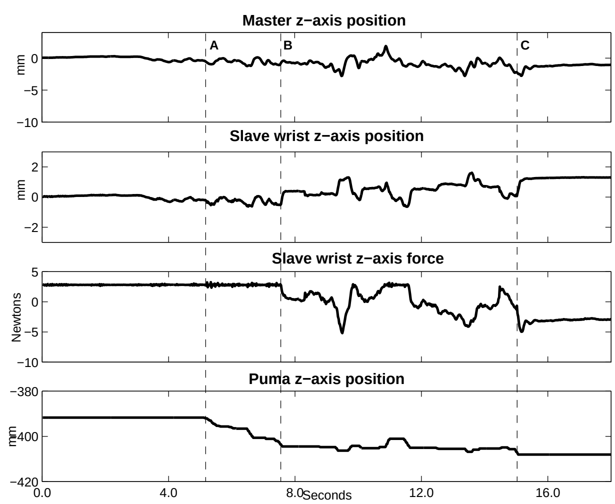

Fig. 12. Z-axis position of master, slave wrist and PUMA and forces on slave wrist during UCF assembly task. A) PUMA moves towards surface. B) Surface contacted. C) Block snaps into place.

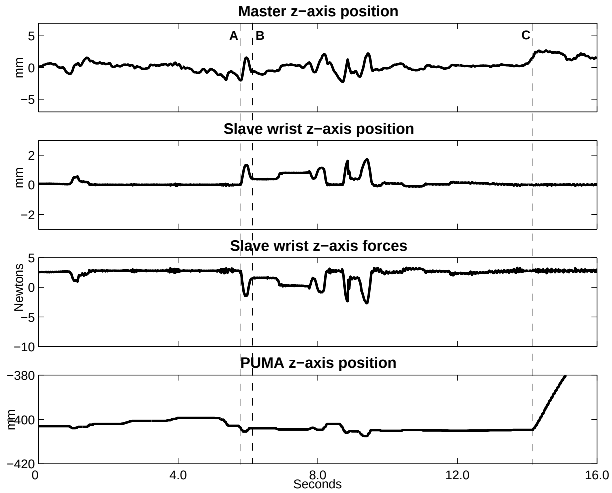

Fig. 13. *Z*-axis position of master, slave wrist and PUMA and forces on slave wrist during MDRC assembly task. A) Block touches surface. B) Block in contact with surface. C) PUMA withdraws from surface after block released.

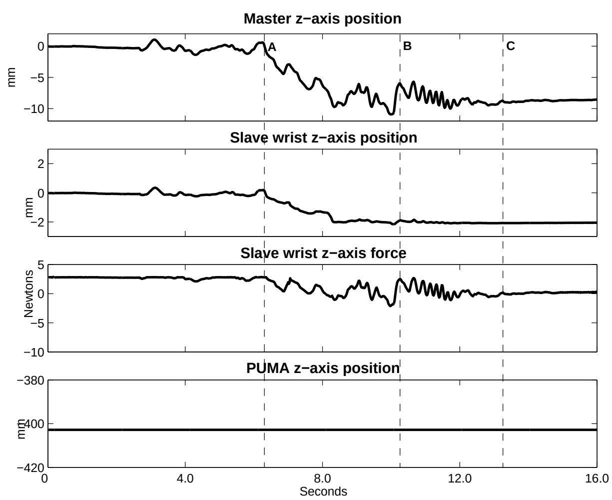

Fig. 14. *Z*-axis position of master, slave wrist and PUMA and forces on slave wrist during SBC assembly task. A) Block contacts surface. B) Block snaps onto surface. C) Block locked to surface. (PUMA is indexed off.)

The SBC task (Fig. 14) shows the user smoothly approaching the surface (A), and snapping the block onto the surface (B) after minimal adjustment. The ability to feel contact forces and to simultaneously make fine adjustments in alignment limits contact time with the surface and reduces force oscillations. This task was accomplished in just one attempt.

V. Conclusion

We have demonstrated a teleoperation system which retains the high frequency and fine positioning capabilites of MLDs while expanding their workspace by several orders of magnitude. UCF mode allows 12-DOF coarse-fine teleoperation using a 6-DOF master without indexing between coarse and fine manipulation. MDRC mode provides 6-DOF coarse telemanipulation using rate control with a compliant wrist. Further study to evaluate trading-off fine position control for force reflection could prove useful. SBC combines coarse-fine manipulation capabilites with bilateral force reflection to allow the user to both manipulate and feel environment details at high resolution. This mode should prove useful in planned psychophysical studies of system transparency. The fine positioning capability available in SBC mode could prove useful in investigating micro-assembly tasks with scaled up force-reflection.

Formal studies of operating parameters such as system position and force bandwidth would help to characterize the system and the haptic feedback it provides [10].

The stability of the system and techniques for cancelling or isolating the effects of PUMA dynamics on the slave wrist motion need further study. Alternative control schemes such as sliding control [11] or impedance control [12], [13] might be implemented.

Acknowledgments

The authors thank Peter Berkelman, Storm Orion, Alex Nicolaidis, Al Rizzi, Jay Gowdy, and Clark Haynes for their valuable contributions. This work was supported in part by National Science Foundation grants IRI-9420869 and IIS-9802191 and an equipment donation from IBM.

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