Mechatronics and Robotics, (MechRob '04)
Aachen, Germany, September 13-15, 2004, pp. 1453-1457.

Teleoperation Mediated Through Magnetic Levitation: Recent Results*

B. J. Unger, R. L. Klatzky, and R. L. Hollis
Robotics Institute
Carnegie Mellon University
Pittsburgh, Pennsylvania, USA
bju@andrew.cmu.edu, klatzky@andrew.cmu.edu, rhollis@cs.cmu.edu

***Abstract*—We present design and performance data for a coarse-fine teleoperation system with bilateral force reflection. The system uses a 6-DOF Lorentz magnetic levitation master device to control a 6-DOF fine-positioning Lorentz magnetic levitation slave device mounted on a 6-DOF PUMA manipulator. This coarse-fine arrangement serves to expand the workspace of the slave device while retaining its frictionless characteristics, high position resolution and high bandwidth. Using this system, we are beginning to perform psychophysical measurements on human operators performing real, virtual, and real-remote 3-D haptic manipulation tasks with each scenario using the same 6-DOF master device. In the virtual task scenario, interactions are rendered haptically from a synthetic model. In the real task scenario, the manipulandum of the haptic device interacts by direct mechanics with a real environment. In the remote-real scenario, interactions with a remote real task environment are mediated through the teleoperation system. In all three scenarios, visual feedback is provided by a graphical display.**

I. INTRODUCTION

The study of haptic feedback for task performance in real and virtual environments has received considerable attention in recent years. Many haptic displays have been tested using various performance criteria.

The fidelity of a particular haptic display is often measured in terms of kinematic and dynamic design constraints such as force bandwidth and dynamic range [3] or frequency response and steady state accuracy. Other tests have concentrated on the operator's ability to perform specified tasks. Analysis of task performance has generally focused on binary failure/completion criteria, accuracy [4] or completion time analysis [5]. Whereas simple measurements of task performance demonstrate gains when haptic feedback is employed, they fail to delineate the underlying strategies used by the subject in attaining the goal. More sophisticated analysis employing force/torque and position/orientation data collected throughout a task provides richer, quantifiable performance metrics.

*Portions of this paper have appeared in [1] and [2].

By examining these data recorded continuously during the procedure, a larger task can be broken into subtasks, allowing quantitative analysis of the effect of different parameters on each subtask. Identification of important subgoals, operator force and position strategies, and the influence of device parameters may then provide guidance for improved interface design and further understanding of the psychophysics of haptics. For example, operator performance during peg-in-hole placement tasks can be studied [6], [7], [8]. Such studies provide a point of reference for the goal of understanding human manipulation strategies.

Performance of tasks involving contact in three dimensions involves discrimination of point, edge and face hard contacts during motion in 6 DOFs. Unger, *et al.* at Carnegie Mellon University have been working to compare task performance in virtual, real, and real-remote (teleoperation) scenarios [8], [9], [1]. For these experiments, it is important that haptic feedback realistically represents complex environments with both rigid and deformable entities. Device limitations, such as stiffness range, position resolution and bandwidth, may result in noticeable deviations from the ideal haptic experience.

The system described in this short paper aims to minimize these effects by using both a master and slave which are high in haptic fidelity. This is achieved by basing both the master and slave 6-DOF devices on Lorentz magnetic levitation.

II. LORENTZ MAGNETIC LEVITATION

A rigid body can be levitated by controlling currents in coils attached to the rigid body, where the coils are immersed in magnetic fields and the position/orientation of the body is measured [10], [11]. We refer to this approach as Lorentz magnetic levitation to distinguish it from the usual approach taken in magnetic bearings which employ Maxwell forces rather than Lorentz forces. Salcudean and Hollis first recognized that devices using Lorentz levitation might provide "ideal" haptic interfaces [12].

Advantages of such devices include 6-DOF motion with a single moving part, complete absence of static friction, wide range of achievable stiffness, high bandwidth, and high motion resolution. A principal disadvantage is small motion range compared with more traditional designs.

Fig. 1. Haptic master and display subsystem in use.

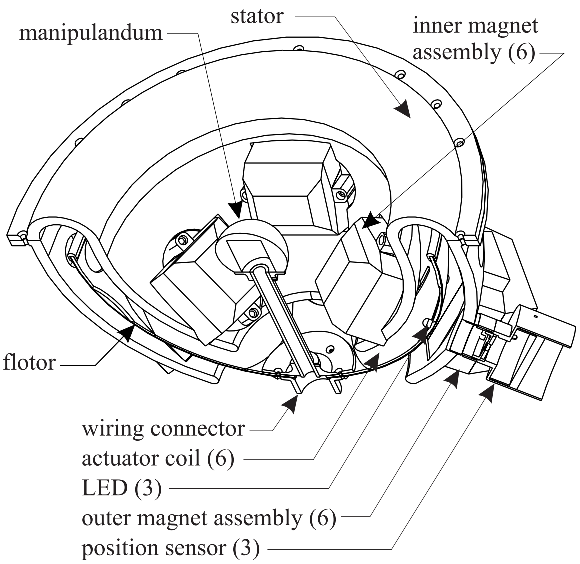

Fig. 2. Lorentz magnetic levitation haptic master cut-away view of design.

Within the Lorentz levitation paradigm, there is a huge space of possible engineering designs which can be applied to many different application tasks. We describe here a particular design that we are using as a teleoperation master, and a different design as a teleoperation slave. Teleoperation with Lorentz levitation devices of yet a different design was first done by Salcudean, *et al.*, at the University of British Columbia [13].

A. Teleoperation master

The haptic master and display subsystem is shown in Fig. 1. The operator views a real video or computed model of the task environment on the monitor. The magnetic levitation haptic master device used in this system is shown in Fig. 2 [14]. The device has a hemispherical actuator assembly, optical position sensors, electronics, and realtime computer.

Fig. 3. Photograph of the Coarse-fine slave subsystem.

The flotor has six coils embedded in a hemispheric aluminum shell enclosed within the stator's fixed magnet assemblies. Current in each coil interacts with the strong magnetic fields of the enclosing magnets to produce six independent Lorentz forces, providing an arbitrary force/torque wrench on the flotor, and hence to the attached manipulandum and the operator's hand. Three LEDs on the flotor imaged by lenses and sensed by fixed optical sensors provide position and orientation information with resolutions of 5-10 μm, depending on position in the workspace. Because of the low flotor mass and freedom from static friction, a position bandwidth of $\sim$125 Hz at $\pm$3 dB is achieved [14]. Maximum stiffness is approximately 25 N/mm in translation and 50.0 Nm/rad in rotation [14]. 6-DOF motion of the handle has a range approximately that of comfortable fingertip motion with the wrist stationary ($\pm$12 mm translation and $\pm 7^\circ$ rotation in all directions).

B. Teleoperation slave

The teleoperation coarse-fine slave subsystem is shown in Fig. 3, and the fine motion slave device in our system is shown in Fig. 4. The IBM Magic Wrist, developed in the late 1980's, 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 capabilities. In our system, the wrist is attached to the tooling mount of a PUMA 560 industrial robot.

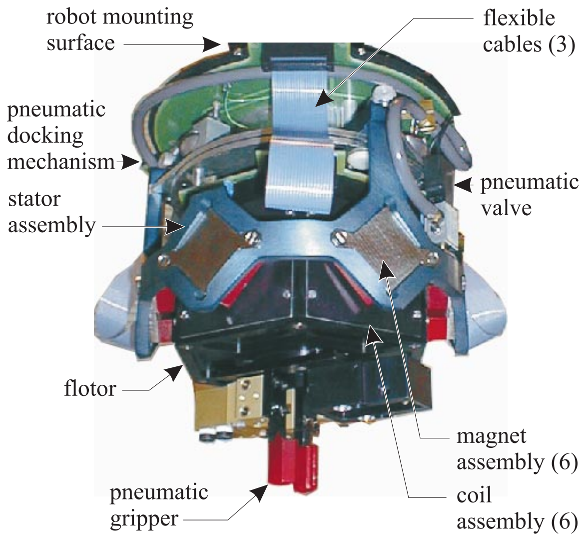

Fig. 4. Photograph of the Magic Wrist slave device.

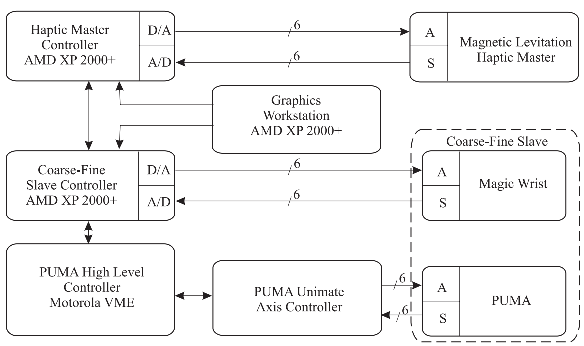

Fig. 5. Data flow between components of the coarse-fine teleoperator system.

The flotor of the Magic Wrist 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 permanent magnet structures of the actuators are attached to inner and outer stators which in turn are attached to the distal link of the robot arm coarse manipulator. The coils of each actuator are contained in the thin, hexagonal flotor shell. The position and orientation of the flotor with respect to the stator is sensed by a triplet of optical beams directly projecting from the stator to a corresponding set of two-axis position-sensing photodiodes (PSDs) attached to the inside of the flotor. A set of three thin flexible ribbon cables provide power and signals to and from 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 bandwidth of around 50 Hz.

C. System Control Modes

Figure 5 shows the principal component blocks of the coarse-fine teleoperator system and the data paths between them, where S indicates sensing and A indicates actuation. Several useful modes of operation have been implemented [2]:

- *Unilateral Fine Teleoperation (UFT)*: slave wrist position/orientation tracks the scaled-down master position/orientation; PUMA coarse positioner is stationary.
- *Unilateral Coarse-Fine Teleoperation (UCF)*: slave wrist moves and PUMA remains stationary while slave wrist is inside of a small workspace region around its zero point; PUMA coarse positioner tracks the center of the slave wrist workspace under rate control while the slave wrist

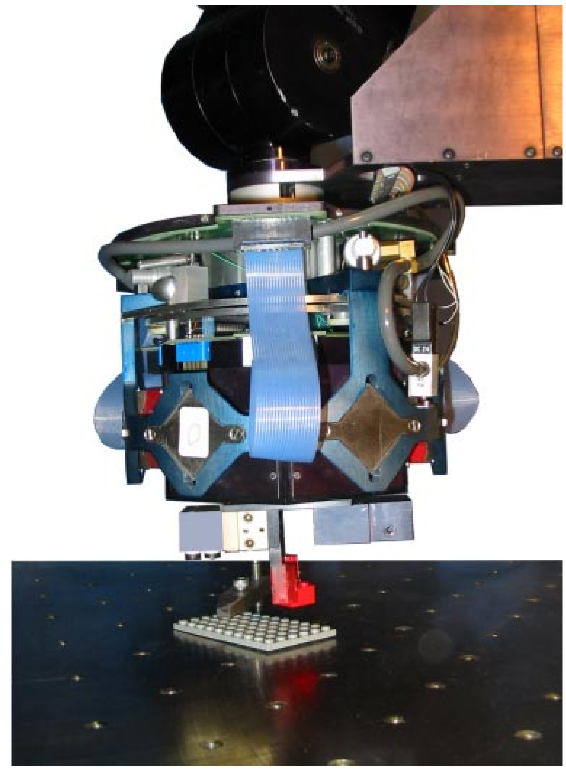

Fig. 6. Wrist and gripper during block placement task.

We have to date obtained quantitative results for a peg-in-hole task in the real and virtual scenarios, and anecdotal results for the remote-real scenario. Preliminary findings indicate that task performance is best in a real environment. 90 trials were recorded for the real task scenario and 89 trials for the virtual task scenario. Operators performed the real peg-in-hole task faster and more accurately than the virtual one. Terminal forces (forces in the last 1s of a trial) applied by operators in both scenarios were not significantly different in any axis. However, the variability of force application during any given trial, as measured by "within trial" terminal force standard deviation (σ), was greater for the virtual haptic task [9]. The teleoperation system has been used successfully in the remote-real scenario to perform a peg-in-hole task. The system is first used in the MRC mode to perform approximate alignment of the peg with the hole and then switched to SBC mode for final alignment. The operator can convincingly feel contact of the peg with the surface and edges around the rim of the hole.

To test the functionality of our system, a simple assembly task was performed using UCF, MRC, and SBC modes. A 4×4 Lego^{TM} block is grasped using the slave wrist's pneumatic gripper. The operator moves the 4×4 block into position above another $\times4$ Lego^{TM} surface, orients the block correctly and snaps it into place (Fig. 6).

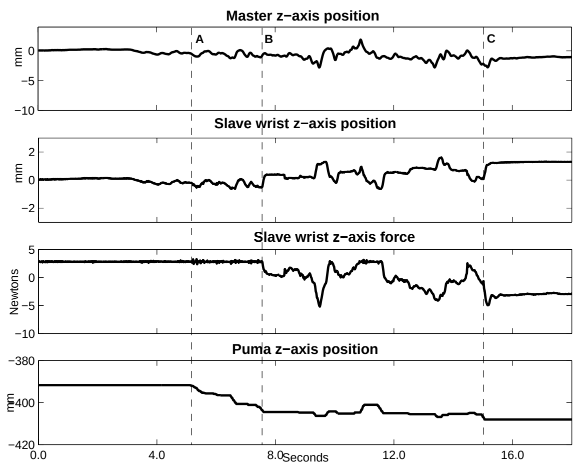

Fig. 7. Task measurements during for the Lego$^{\text{TM}}$ assembly task in UCF mode. At Event A, the PUMA starts moving toward the target block; at Event B the surfaces contact; at Event C the blocks snap into place.

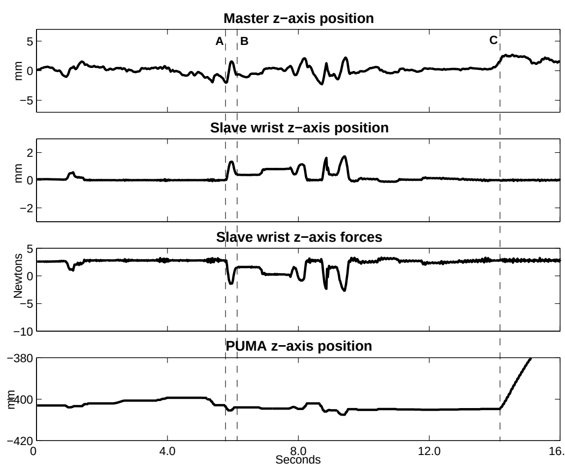

Fig. 8. Task measurements during for the Lego$^{\text{TM}}$ assembly task in MRC mode. At Event A, the blocks are contacting; beginning at Event B the blocks are snapped together; at Event C the PUMA withdraws after the block is released.

During UCF mode operation, there is no force reflection and the operator must rely on the displayed model (or direct visual observation) to perform the task. Both of the MRC and SBC modes provide force reflection, however MRC permits only coarse motion while the SBC mode allows both coarse and fine motions. Operators should therefore find the task harder in UCF and MRC modes than in SBC mode. We surmise that the greater difficulty may result in longer task completion times and higher applied forces, but this is not yet formally characterized.

Representative z-axis position and force data is shown in Figs. 7, 8 and 9. In these figures, it is seen that the z-axis force in all three modes remains fairly constant, counteracting gravity, prior to contact between the blocks. In the UCF task (Fig. 7) several large force oscillations occur prior to the block snapping into place, since the operator is working with visual feedback alone.

During the MRC task (Fig. 8), the operator contacts the surface (Event A) vigorously and large oscillations in force occur. The PUMA's lack of fine position control prevents the operator from making gentle contact and once attached (Event B) the block is pulled up again as the operator struggles with the coarse control of the PUMA. It should be noted that in

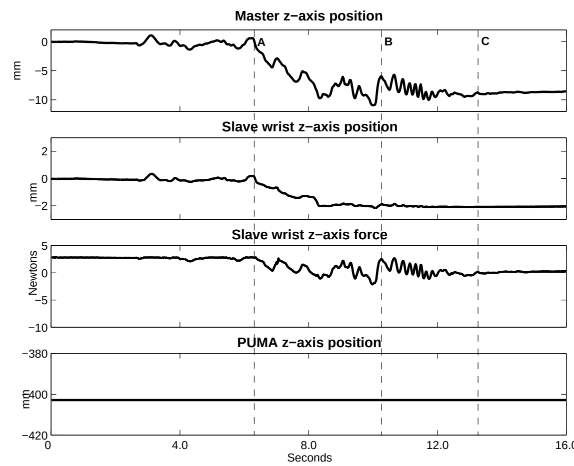

Fig. 9. Task measurements during for the Lego$^{\text{TM}}$ assembly task in SBC mode. At Event A, the blocks are contacting; at Event B the blocks snap together; at Event C, the PUMA is indexed off.

Attribute	**UBC system**	**Present system**
Coarse positioner	CRS A460	PUMA 560
Master translation	±4.5 mm	±12.5 mm
Master rotation	±6°	±7°
Master position resolution	5 μm	5-10 μm
Master position bandwidth	30 Hz	125 Hz
Master force/torque sensor	JR3	none
Master servo rate	500 Hz	4 kHz
Slave translation	±4.5 mm	±5 mm
Slave rotation	±6°	±4°
Slave position resolution	5 μm	1 μm
Slave position bandwidth	30 Hz	50 Hz
Slave force/torque sensor	JR3	none
Slave docking	none	pneumatic
Slave gripper	none	pneumatic
Slave Servo rate	500 Hz	4 kHz

TABLE I

COMPARISONS BETWEEN THE UBC TELEOPERATION SYSTEM [13] AND THE SYSTEM DESCRIBED IN THIS PAPER [14], [1]

.

Whereas the range of motion of the magnetic levitation master (±12.5 mm and ±7° in the present device) has over 20 times the workspace volume of the UBC master, it is still quite small compared with traditional haptic masters. This makes the master less suitable when it is required that hand motion for the remote task must reflect the master motion one for one. On the other hand, the master's high motion resolution (5-10 μm depending on position in the workspace) makes it straightforward to scale motion by a factor of 10 or so. For example, we have found it easy to perform tasks with motions the size of the display screen while working in a virtual environment. This corresponds to the typical mouse user's experience that mouse movement is much smaller than display size. We have found that scaling, indexing, and rate control work well for both virtual and real remote environments. The small workspace of the magnetic levitation slave is not a problem since it is mounted on the coarse positioner (robot arm) thus creating a large workspace slave subsystem with very high motion resolution and low effective mass. This arrangement provides the operator with a very high fidelity impression of subtle friction and texture attributes of the remote environment.

The design of our system is not optimal, and many improvements could be made to the master, robot, and slave subsystems. We are currently designing and fabricating a batch of improved magnetic levitation master devices which will have greater motion range, higher bandwidths, and better usability. The slave Magic Wrist's weight could easily be reduced, and its motion range and payload capacity could be increased. The PUMA 560 and its controller are far from ideal as a coarse positioner.

In fact, it is important to realize that within the Lorentz levitation approach [11], there is a wide spectrum of actuator layout, sensing, and control choices. This would enable systems to be developed tailer-made for specific applications. For example, it is not necessary for all actuators and sensors to be bundled tightly together as in the system described here. Rather, they could be distributed around a large structure. Such configurations would have great utility for teleoperation and vibration isolation in space applications.

Given the several important performance advantages of teleoperation systems mediated through magnetic levitation as shown here and in [13], it is perhaps surprising that so far more systems have not been built. We believe that this is in part due to i) the software and hardware complexity and cost inherent in an 18-DOF system, ii) the difficulty in optimizing the overall design of such a system, and iii) the lack of a "killer app" that can economically take advantage of its performance. Nevertheless, we are optimistic that in the not too distant future systems based on Lorentz levitation will find use in many fields.

Acknowledgments

This work was supported in part by National Science Foundation grants IRI-9420869 and IIS-9802191 and an equipment donation from IBM.

References

[1] B.J. Unger, R.L. Klatzky, and R.L. Hollis. A telemanipulation system for psychophysical investigation of haptic interaction. In *IEEE Int'l. Conf. on Robotics and Automation*, pages 1253–1259, Taipei, Taiwan, September 16-18 2003.

[2] B. J. Unger and R. L. Hollis. Design and operation of a force-reflecting magnetic levitation coarse-fine teleoperation system. In *IEEE Int'l. Conf. on Robotics and Automation*, New Orleans, April 26 - May 1 2004.

[3] R. Ellis, O. Ismaeil, and M. Lipsett. Design and evaluation of a high-performance haptic interface. *Robotica*, 14:321–327, 1996.

[4] P.Richard, A. Kheddar, and R. England. Human performance evaluation of two handle haptic devices in a dextrous virtual telemanipulation task. *Proceeding of the 1999 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 1543–1548, 1999.

[5] P. Buttolo, D. Kung, and B. Hannaford. Manipulation in real, virtual and remote environments. *Proceedings IEEE Conference on System, Man and Cybernetics*, 5:4656–61, October 1995.

[6] B. Hannaford, L. Wood, D. McAffee, and H. Zak. Performance evaluation of a six-axis generalized force-reflecting teleoperator. *IEEE Transactions on Systems, Man, and Cybernetics*, 21(3), May/June 1991.

[7] T. Yoshikawa and K. Yoshimoto. Haptic simulation of assembly operation in virtual environment. In *Proc. ASME Dynamic Systems and Control Division*, volume 69-2, pages 1191–1198. ASME, 2000.

[8] B. J. Unger, A. Nicolaidis, P. J. Berkelman, A. Thompson, R. L. Klatzky, and R. L. Hollis. Comparison of 3-D haptic peg-in-hole tasks in real and virtual environments. In *Proc. Int'l. Symp. on Intelligent Robots and Systems*, Maui, Hawaii, Oct. 29—Nov. 3 2001.

[9] B. J. Unger, A. Nicolaidis, P. J. Berkelman, A. Thompson, S. Lederman, R. L. Klatzky, and R. L. Hollis. Virtual peg-in-hole performance using a 6-DOF magnetic levitation haptic device: Comparison with real forces and visual guidance alone. In *10th Int'l. Symp. on Haptic Interfaces for Virtual Environments and Teleoperator Systems*, pages 263–270, Orlando, FL, March 2002.

[10] R. L. Hollis. Six DOF magnetically levitated fine motion device with programmable compliance. U.S. Patent #4,874,998, October 17 1989.

[11] R. L. Hollis and S. E. Salcudean. Lorentz levitation technology: a new approach to fine motion robotics, teleoperation, haptic interfaces, and vibration isolation. In *Proc. 6th Int'l Symposium on Robotics Research*, Hidden Valley, PA, October 2-5 1993.

[12] R. L. Hollis and S. E. Salcudean. Input/output system for computer user interface using magnetic levitation. U.S. Patent 5,146,566, September 8 1992.

[13] S. E. Salcudean, N. M. Wong, and R. L. Hollis. Design and control of a force-reflecting teleoperation system with magnetically levitated master and wrist. *IEEE Trans. on Robotics and Automation*, 11(6):844–858, December 1995.

[14] P. J. Berkelman and R. L. Hollis. Lorentz magnetic levitation for haptic interaction: Device design, performance, and interaction with physical simulations. *Int'l. J. of Robotics Research*, 19(7):644–667, July 2000.