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CONTROL ISSUES RELATED TO BILATERAL TELEOPERATIONS OF LONG-REACH, FLEXIBLE MANIPULATORS *

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CONTROL ISSUES RELATED TO BILATERAL TELEOPERATION OF LONG-REACH, FLEXIBLE MANIPULATORS*

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ABSTRACT

A challenging problem presently being addressed by the Department of Energy (DOE) is the extraction of large volumes of hazardous waste from underground waste storage facilities. The nature of the material requires the use of robotic and teleoperated systems. Furthermore, the constraints of the storage tanks require the use of long reach manipulators.[1] These robots are characterized by their large workspace and reduced mass. Unfortunately, this reduction in mass increases structural compliance, making these robots susceptible to vibration. Until recently, no attempt has been made to provide the operator any type of force reflection due to the compliance of the slave robot. This paper addresses the control of bilateral teleoperation systems that use long-reach, flexible manipulators. Analysis and experiments show that the compliance of the slave robot directly affects the stability of the teleoperation system. This study suggests that this may be controlled by increasing the damping on the master robot. However, this increase in target damping increases the energy an operator must exert during the execution of a task. A new teleoperation strategy adapts the target impedance of the master robot to variations in the identified impedance of the remote environment coupled to the slave robot. Experiments show increased performance due to a decrease in the energy the operator must provide during task execution.

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I. INTRODUCTION

Many teleoperation systems consist of a master and slave manipulator that are approximately the same size. New applications, such as micromanipulation and space-based assembly, require motion and force scaling between the master and slave robots.[2] The research described in this paper focuses on teleoperation systems that require motion amplification between the master and slave robots. In particular, we focus on force-reflecting teleoperation of long-reach, flexible manipulators. First, the impact of robot compliance on the stability of force reflection is considered. This provides the motivation for adaptation of the master robot impedance with respect to the environment manipulated by the slave. Experiments show improved performance based upon measurement of energy provided by the operator during task execution.

II. LONG-REACH TELEOPERATION

The teleoperation system used for this investigation consists of a master robot scaled to human arm motion and a slave robot, shown in Figure 1, that has a workspace approximately 50 times the master robot's workspace. This configuration is reprentative of teleoperation systems used for space-based assembly and nuclear waste remediation. The test bed simulates this real world scenario and provides further insight into remote manipulation using long-reach manipulators. To isolate the human operator from the slave environment, the master and slave robots are located in different labs in the same building. This configuration allows the investigators to control the visual, acoustic, and tactile cues that the operator experiences.

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A. Teleoperation Testbed

The control of compliant manipulators has been a topic of active research for the past 20 years.[3] The slave robot used in this investigation, RALF (Robotic Arm Long and Flexible), is a 2-DOF long-reach manipulator that may be indicative of possible designs used in the nuclear waste restoration process. It consists of two cylindrical links with a span of approximately 3-m each and has a payload capacity of 260-N while its link weight is only 450-N.[4] A modular scaffold next to the slave robot permits simple modifications to the slave robot's environment. This task board can be configured for tasks such as teleoperated pick-and-place, constrained manipulation, remote path following, and basic assembly such as the peg-in-the-hole insertion problem. The operator views the motion of RALF on two monitors that display black and white camera views of the slave robot's workspace. The first camera view, displayed on a 63-cm diagonal monitor, records a 6-by 4.5-m vertical plane of motion from the side with a line of sight perpendicular to the robot's plane of motion. The second camera is mounted at the tip of the second link of RALF. This provides visual feedback of the robot's end-effector. A 22-cm diagonal monitor displays roughly a 35- by 25-cm rectangle in the plane of the end-effector.

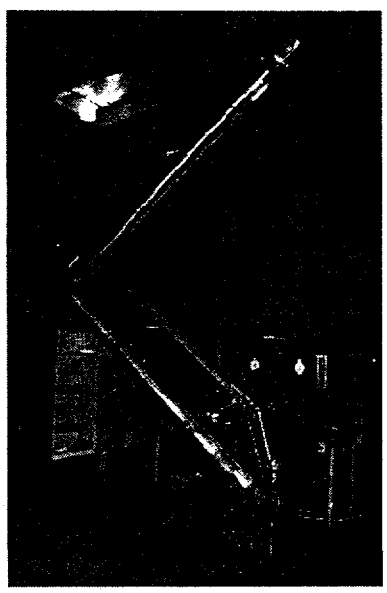

Figure 1. Long Reach Manipulator

B. Master Robot Control

The master robot, HURBIRT (Human Robot Bilateral Research Tool), is a 2-DOF impedance-controlled robot scaled to human arm motion.[5] To facilitate the teleoperation tasks, the controller for HURBIRT computes and scales its tip position from the space of the master robot to the space of the slave, RALF. Currently, a 7:1 position amplification permits comfortable mapping of RALF's full workspace into the workspace of the human operator. Once the desired tip position for RALF is calculated, the desired joint position vector is computed and then transmitted to the VME bus for input to the slave robot's controller. Currently, data are transmitted via a high-speed serial communication port every 10-ms at 38,400 baud.

HURBIRT uses a computed torque impedance controller. One example of the target impedance of the master robot is illustrated in Figure 2. The workspaces of the master and slave manipulators in Figure 1 are dissimilar. Simple tasks such as moving the slave robot to its home position prove to be difficult by visual cues alone. The target impedance of the master robot, using the same philosophy of superimposing impedances described by Hogan, is augmented with virtual walls that constrain the operator from commanding the slave robot outside its workspace.[6] The target impedance for the robot is defined in Eq. (1).

$$M_t\ddot{x} + B_t\dot{x} + F_{vf} = F_h \qquad (1)$$

The target mass and damping matrices, M_t and B_t respectively, control the ease with which the operator moves the master robot. The two external stimuli to the master robot include the human applied force, F_h, and the interaction force between the slave robot and its environment, F_e. The scale, A, is the motion amplification between the master and slave robots. An additional virtual force, F_{vf}, represents the repulsive force produced by deforming the virtual fixtures, in this case stiff walls constraining the effective workspace of the master robot. Four compliant circles, mapped inside the master robot's workspace, replicate the limits of the slave robot's workspace. If the operator manipulates inside the scaled slave robot's workspace, the robot effectively "feels" like a mass moving through a viscous fluid. However, if the human attempts to command the robot outside its workspace, the virtual walls push the operator back into the workspace. Extensions of this example can include sophisticated forms of obstacle avoidance. Equation (2) provides a model of HURBIRT's dynamic equations of motion with respect to the generalized coordinates, q. This model includes the inertial matrix, D(q), the gravitational load, $\phi(q)$, and the damping and nonlinear velocity terms, $C(q,\dot{q})\dot{q}$. Forces applied to the robot include the joint torque, τ, and the human applied force, F_h, projected to the generalized coordinates through the transpose of the Jacobian, J(q).

$$D(q)\ddot{q} + C(q,\dot{q})\dot{q} + \phi(q) = \tau + J^t(q)F_h \qquad (2)$$

The control law in Eq. (3) provides the torque required to compensate for the robot's natural dynamics as well as provide the target impedance in Eq. (2).

$$\tau = D(q)\ddot{q}\,J^{-1}(q)\left\{M_t^{-1}\left[F_h + \frac{1}{A}F_e - F_{vf} - B\dot{x}\right] - \dot{J}(q)\dot{q}\right\} + C(q,\dot{q})\dot{q} + \phi(q) - J^{t}(q)F_h \qquad (3)$$

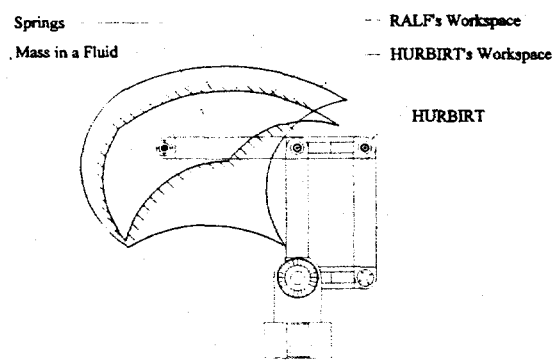

Figure 2. Impedance-controlled master robot

C. Teleoperation Workspace and Task

A vertical board, representing a wall in the remote environment, is attached to the task board in the slave robot's workspace. Markers on the wall indicate a path the operator is to follow during the execution of the teleoperated task. Furthermore, the operator is to attempt to maintain constant pressure on the wall while moving along this path. The operator begins the task by moving the slave robot from its home position to the top of the wall. After contact is established, the operator moves vertically down the surface of the wall while trying to maintain a constant contact force. After completing the path, the operator maneuvers the robot back to the home position. When the operator starts the task, he initializes the criteria measured during the execution of the task. These criteria include the task execution time, the power provided by the human to the master robot, and the net interaction force at the tip of the slave and master robot.

III. STABILITY OF BILATERAL TELEOPERATION

The problems associated with bilateral teleoperation of flexible manipulators reflect similar trends of problems described in bilateral teleoperation systems with time delays. The slave robot's mechanical compliance produces time delays in the form of wave propagation between the joint actuators and force sensor at the end of the robot. This produces an effective delay between human action and tip motion. A survey of bilateral teleoperation systems with time delays provides some explanation of the problems and potential solutions to bilateral teleoperation of compliant manipulators. Ferrel described stability limitations of bilateral teleoperation systems with transmission delays between the master and slave manipulators.[7] Delays beyond 300-ms potentially destabilize a bilateral teleoperation system. If forces are fed back to the operator, who also provides the position command to the slave, they will tend to move the operator's hand. With excessive delays, the feedback is not only a source of information, but may act as a disturbance as well. This closed system, just as any closed loop system with long delays, can become uncontrollable. Systems with purely visual feedback can avoid instability by adopting a move and wait strategy. Unfortunately, this philosophy does not work well with tasks that require contact between the slave robot and its environment. Vertut et al. address stability and propose limiting the velocities of the system and reducing the bandwidth to stabilize a bilateral teleoperation system with time delays.[8] Hannaford and Anderson show through experimentation that additional damping at the master robot stabilizes teleoperation systems during collision with stiff environments.[9] Operators reported that the system felt viscous and unresponsive. They suggest some form of on-line adaptation to adjust the damping of the master robot.

Figure 3 illustrates a simplified block diagram of the teleoperation system. A flexible manipulator is a distributed parameter system that has, theoretically, infinite degrees of freedom. Furthermore, the link compliance produces nonminimum phase zeros in the robot's transfer function between joint actuation and tip force sensors. For our stability analysis, we truncate the model of the flexible manipulator and include only the first mode of vibration. RALF's first natural frequency is 4.5 Hz with a damping ratio of approximately 0.05. This is approximated by a second order system with a mass of 5.7-kg, viscous damping of 17-N-m^{-1}s and stiffness of 5000-N/m. In the following experiments, the environment has a stiffness of approximately 2000-N/m. Furthermore, the master robot has a target mass of 10-kg. Figure 4 illustrates the locus of the system's closed loop poles as the target damping of the master robot increases from zero to infinity. This exercise is not intended to predict instability as much as to illustrate trends in the system's stability based upon the master robot's target impedance. Evidently, the stability of the teleoperation system can be controlled by adjusting the target damping of the master robot. Furthermore, as the environment stiffness increases, higher target damping of the master robot is required.

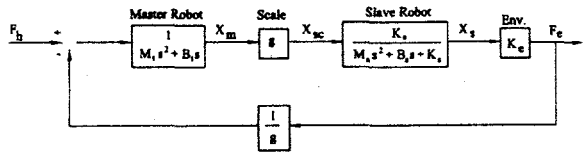

Figure 3. Teleoperation block diagram

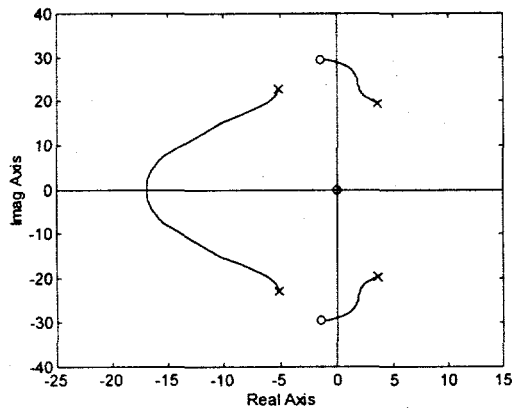

Figure 4. Locus of closed loop poles varying B_t

IV. EFFECT OF MASTER IMPEDANCE

A. Fixed Target Impedance

The following section describes the effect the master robot impedance has on the performance of the bilateral system. The first bilateral teleoperation experiment has a fixed target impedance on the master robot. The target impedance of the master robot has high target damping to ensure stability during contact with the environment. For this series of experiments, the target impedance in Eq. (1) has a 10-kg diagonal mass matrix with a 167-$Nm^{-1}s$ diagonal damping matrix. Figure 5 illustrates the motion profile of the task. After 20 repetitions of the task, the mean power provided by the human to the master robot is 148-J with a variance of 11.8-J. Likewise, the mean integrated force at the slave robot is 129.9-N-s with a variance of 8.9-N-s.

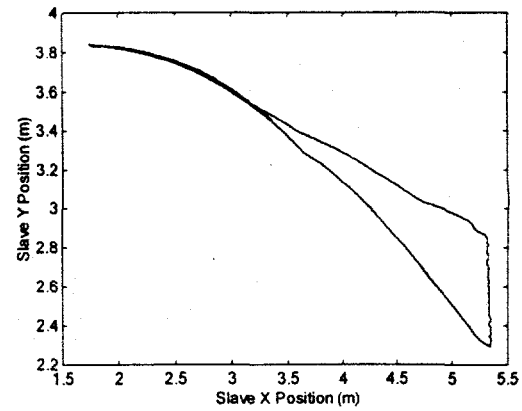

Figure 5. Slave motion during teleoperated task

While the high damping ensures stability during contact, it increases the effort an operator must exert during task execution. Lower master damping can reduce this effort, but the stability analysis suggests that this can potentially drive the bilateral teleoperation system unstable. This provides the motivation for an adaptive impedance controller that adapts to variations in the slave's environment.

B. Remote Environment Estimation

When the slave robot is unconstrained, the viscous resistance of the master robot should be light to reduce the load on the operator.[9] However, when the slave robot approaches a constraint surface, the target damping on the master robot should increase to provide stable bilateral teleoperation. Love and Book describe a method of identifying the dynamic characteristics of a robot's environment.[10] One approach to modeling a position dependent representation of a robot's environment is to discretize the robot's workspace. Each of these discrete cells, illustrated in Figure 6, represents a small volume of the robot's workspace. The objective is to use these cells as position dependent storage units for the results of a recursive environment estimation process. A multi-input, multi-output, recursive least-squares algorithm (MIMO-RLS), using tip force and position information, estimates the dynamic characteristics of the robot's environment. After each cycle of the estimation process, the updated parameters of the environment model are averaged with previous results and stored in the cell that corresponds to the current tip position of the robot. To provide adequate resolution without excessive memory requirements, a 100 by 100 element array is used to model the slave robot's workspace. Each element of the two-dimensional array corresponds to a 7-cm^2 square area of the slave robot's workspace. Figure 7 illustrates the basic process executed each cycle of the estimation routine. The tip force and position vectors are measured and filtered through the RLS algorithm, which provides an updated estimate of the

environment mass, damping, and stiffness matrices. At the same time, the current tip position of the robot is correlated with a cell whose contents are extracted from memory. The parameters stored in the cell corresponding to the current tip position of the robot are updated with the latest estimate of the environment parameters. This provides a time-varying position-dependent model of the environment dynamics.

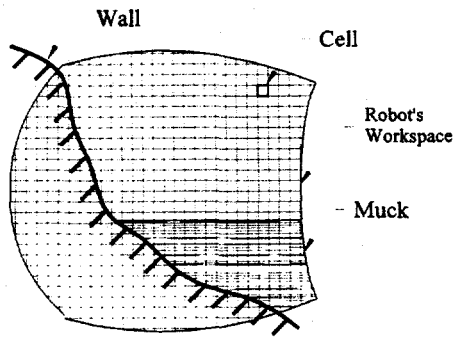

Figure 6. Discretized environment

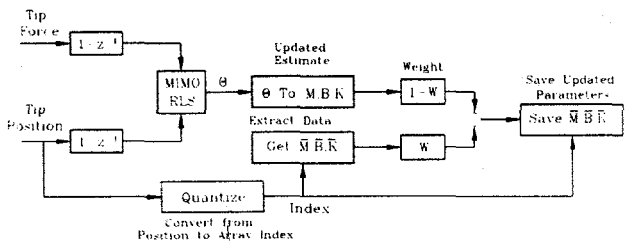

Figure 7. Learing algorithm

D. Remotely Adapting Impedance Control

This section describes a new approach to adapting the target impedance of the master robot based upon an on-line estimation of the remote environment coupled to a flexible robot. The target impedance of the master robot adapts to variations in the identified impedance of a remote environment being operated on by a slave robot. The damping for the target impedance of the master robot is defined in Eq. (4). The damping ratio, ζ_t, is set to 1.0 to minimize vibration during contact with the environment. The index n_x and n_y correlate the tip position of the master robot to the discretized workspace.

$$B_t = 2\zeta_t\sqrt{M_t K_e(n_x, n_y)} \qquad (4)$$

High environment impedance is assumed when the operator maneuvers the slave robot into a region where high uncertainty exists in the environment estimation. As the robot maneuvers through this region, the environment estimation updates the model of the remote environment. As this estimate improves, the target impedance of the master robot adjusts appropriately. Consider the limiting case where the slave robot moves through unconstrained space. As the robot first moves through this space, the teleoperation system assumes the environment has a high stiffness value. This is accomplished by initializing the environment stiffness in each of the cells of Figure 6 to a high default value. If the robot is unconstrained, this stiffness gradually converges to zero, decreasing the target damping in this region. This target damping has a lower threshold of 10-N-m^{-1}s.

Figure 8 illustrates the resulting K_{XX} stiffness grid after 10 repetitions of the task. Evidently, there is a region of space in which the estimated environment stiffness is negligible. This region coincides with the unconstrained space that the robot maneuvers through during the execution of the task. Each cell is initialized with a stiffness of 700-N/m. This ensures that when the slave robot moves into a new region, the adapted target impedance is the same as the target impedance used in the fixed impedance bilateral teleoperation experiments with B_t=167-N-m^{-1}s. As the robot moves through unconstrained space, these cells converge to zero stiffness, reducing the target damping of the master robot's impedance controller. Thus, the robot adapts its damping based upon the remote environment impedance. If the operator attempts to maneuver into a new region, the viscous resistance of the master robot increases in concert with the default high environmental stiffness values. Likewise, regions with high stiffness provide higher damping on the master robot.

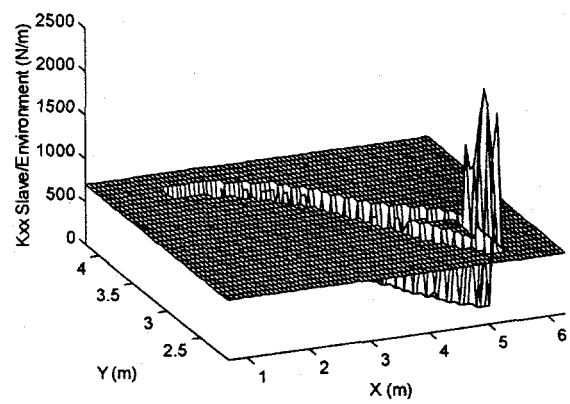

Figure 8: Identified remote environment stiffness

The same series of experiments are conducted using the adaptive impedance control paradigm. After 20 repetitions of the task, the mean energy provided by the human to the master robot is 59.6-J with a variance of 10.1-J. Concurrently, the mean integrated force at the slave robot is 124.3-N-s with a variance of 7.9-N-s. The flexibility of the slave robot and environment is most evident in the force profiles recorded during the task.

Figures 9 and 10 illustrate the external force due to the environment on the slave as well as the human applied force on the master. After the robot contacts the wall, a low-frequency vibration is generated. Because of the force feedback to the master robot, the operator feels this vibration but is capable of maintaining contact and completing the task.

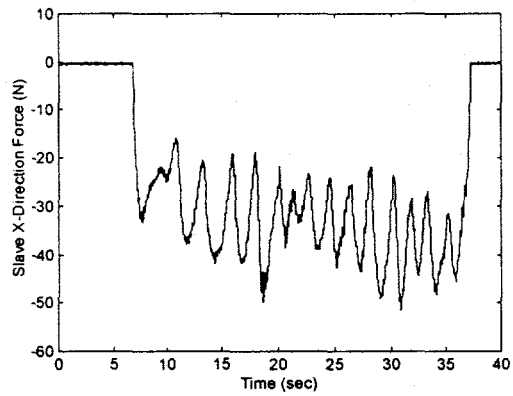

Figure 9. Slave/environment interaction force

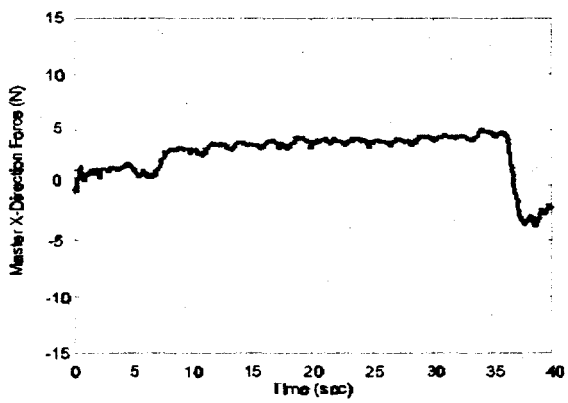

Figure 10. Human applied force

E. Comparison of Fixed and Adaptive Teleoperation

A quantitative comparison of the two bilateral teleoperation systems provides insight into the potential for adaptive bilateral teleoperation systems. The only difference between the teleoperation experiments is the addition of the adaptive damping based upon estimated environment impedance. The initial stiffness of 700-N/m ensures that the adaptive impedance controller has the same target impedance as the fixed impedance when the slave robot maneuvers into a new region. An operator executed the task 20 times, first using the adaptive teleoperation system. Next, the same operator executed the same task 20 times using the fixed impedance teleoperation scheme. Figures 11 and 12 illustrate the task execution time and the integrated force in the remote environment. From these displays, it appears that the remote task is executed with approximately the same proficiency when using either fixed or adaptive impedance control on the master robot.

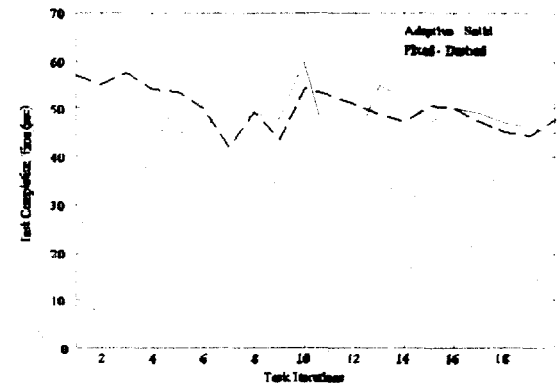

Figure 11. Task completion time

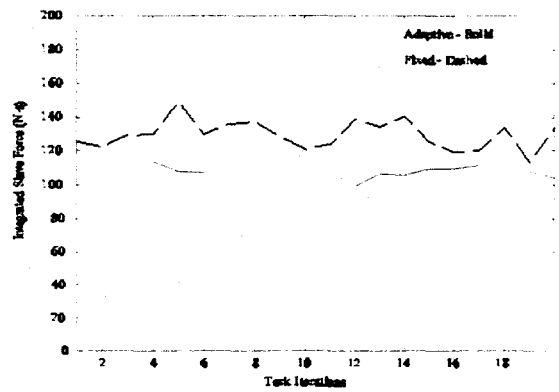

Figure 12. Integrated slave/environment interaction force

Figure 13 and 14 compare the human applied energy and the integrated interaction force at the master robot using fixed and adaptive impedance control. Based on these displays, we see that, for both master arm controllers, the task is performed with approximately the same level of forces, indicating comparable task performance. A comparison of these figures suggests that less energy is required of the human to complete the same task. This reduction in energy reduces the potential for fatigue during repetitive teleoperated tasks.

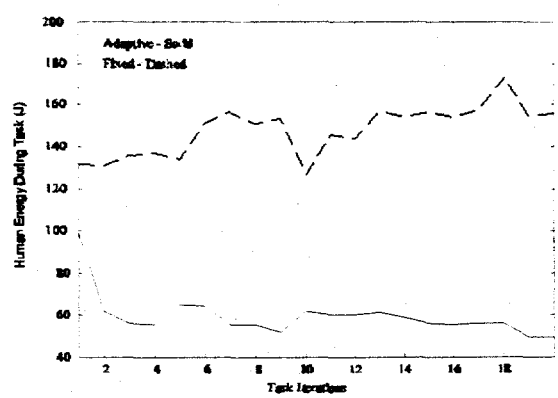

Figure 13. Human applied power

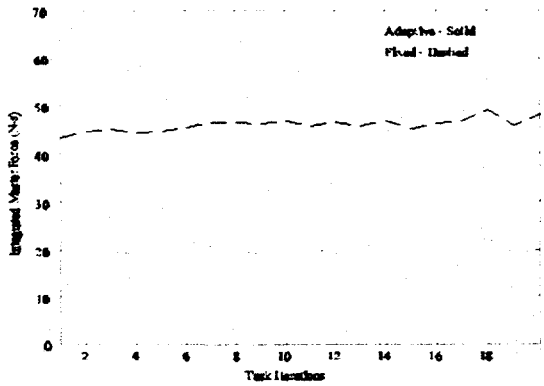

Figure 14. Integrated human/master interaction force

V. CONCLUSION

Impedance control provides a pragmatic approach to controlling the resistance of a robot coupled to a human. First, synthetic or virtual fixtures using potential fields provide a clear method of restricting the motion of a human during teleoperation. This research describes a novel approach to restricting the workspace of a master robot to the scaled workspace of a slave robot that contains a different workspace. One useful consequence of impedance control is the additive property of impedances. If the slave robot's workspace contains obstacles or restricted regions, additional potential fields can be added to the master robot's impedance controller. These potential fields provide resistance when the operator maneuvers the master robot toward these regions.

The versatility of impedance superposition is demonstrated through the described adaptive impedance control methods. A method for modeling and identifying a slave robot's environment is described. This model provides valuable information that improves the performance of bilateral teleoperation systems. One approach to adapting the target impedance of the master robot is to control the damping ratio of the master robot. Adapting the target impedance to variations in the slave robot's environment can reduce the operator's energy, and thus reduce fatigue, during the execution of a task. During static contact experiments, no vibration is evident because of the flexibility of the slave robot. However, during contact hybrid force/motion tasks, a low-frequency vibration is generated at the slave robot that propagates back to the operators. Future work will focus on vibration suppression techniques for the flexible robot and their role in bilateral teleoperation.

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REFERENCES

[1] Kreig, S., Jenkins, W., Leist, K., Squires, K., Thompson, J., Single-Shell Tank Waste Retrieval Study, Westinghouse Hanford Co. Report for the U.S. Department of Energy, 1990.

[2] Colgate, E., "Power and Impedance Scaling in Bilateral Manipulation," *Proceedings of the IEEE International Conference on Robotics and Automation*, pp. 2292-2297, 1991.

[3] Book, W., "Controlled Motion in an Elastic World," *Journal of Dynamic Systems, Measurement, and Control*, Vol. 115, No. 2B, pp. 252-261, 1993.

[4] Huggins, J., Kwon, D., Lee, J., and Book, W., "Alternate Modeling and Verification Techniques for a Large Flexible Arm," *Proceedings of the Conference on Applied Motion Control*, pp. 157-164, 1987.

[5] Love, L., and Book, W., "Design and Control of a Multiple Degree of Freedom Haptic Interface," *Proceedings of the ASME-Winter Annual Meeting, Dynamic Systems and Control*, pp. 851-856, 1994.

[6] Hogan, N., "Impedance Control: An Approach to Manipulation," *ASME Journal of Dynamic Systems, Measuremen., and Control*, Vol. 107, pp. 17-24, 1985.

[7] Ferrell, W., "Delayed Force Feedback," *Human Factors*, pp. 449-455, 1966.

[8] Vertut, J., Micaelli, A., Marchal, P., and Guittet, J., "Short Transmission Delay on a Force Reflective Bilateral Manipulator," *Proceedings of the 4th Symposium on Theory and Practice of Robotics and Manipulation*, pp. 269-285, 1981.

[9] Hannaford, B., and Anderson, R., "Experimental and Simulation Studies of Hard Contact in Force Reflecting Teleoperation," *Proceedings of the IEEE International Conference on Robotics and Automation*, pp. 584-589, 1988.

[10] Love, L., and Book, W., "Environment Estimation for Enhanced Impedance Control," *Proceedings of the IEEE International Conference on Robotics and Automation*, pp. 1854-1859, 1994.