**Proceedings of IMECE2007**
**2007 ASME International Mechanical Engineering Congress and Exposition**
**November 11-15, 2007, Seattle, Washington, USA**

# IMECE2007-41515

# EXPERIMENTS IN LOCAL FORCE FEEDBACK FOR HIGH-INERTIA, HIGH-FRICTION TELEROBOTIC SYSTEMS

**Pete Shull***
Stanford Telerobotics Laboratory
Department of Mechanical Engineering
Stanford University
Stanford, California 94305
Email: pshull@stanford.edu

**Günter Niemeyer**
Stanford Telerobotics Laboratory
Department of Mechanical Engineering
Stanford University
Stanford, California 94305

## ABSTRACT

*Many telerobotic systems include a slave robot with much larger inertial and frictional properties than the master robot and/or a non-backdrivable slave acting as an admittance device. Passive controllers, which are known for their stability and robustness, display the large dynamic forces to the user and/or become insensitive to contact forces. In effect, the user feels the large inertia and friction of the slave robot but does not feel the force of the environment.*

*Force sensors can isolate the environment forces. In this paper, we experiment with local force feedback for an admittance type slave robot. We use the local controller to convert the slave to an apparent impedance device, restoring its sensitivity to environment forces. This will allow the application of stable passive teleoperation controllers. The control structure is validated on a single axis of a large, non-backdrivable, industrial Adept robot operating as a slave in contact and in free space.*

## INTRODUCTION

The goal of telerobotics is to transmit the interactions of a slave robot with a remote environment to the fingertips of a user manipulating a master robot. A successful telerobotic system is both stable and to some degree transparent. Many control architectures have been proposed which seek to achieve these aims including: a passivity-based controller for guaranteeing stability [1, 2], position-force controllers for accurately displaying environment forces directly to the user, a 4-channel architecture for achieving transparency [3], and a 4-channel architecture with local force feedback [4]. For a comparative survey of these and other telerobotic control architectures see [5].

In many telerobotic systems the slave robot has much higher inertial and frictional properties than the master robot. This is true for applications requiring the slave to manipulate large objects or to operate in hazardous environments (e.g. space telerobotics, deep sea telerobotics, industrial robotics). The high inertial and frictional properties of the slave can create large dynamic forces that can overshadow environment forces, making the robot insensitive and dangerous to the environment.

Force feedback can be used to combat these effects. If the force signal is fed back directly to the master, however, stability issues arise and are exacerbated by the presence of time delays. Even without delays, the force scaling will be limited by the mass ratio [6]. Further challenges arise due to the large variation in environment stiffnesses, which may be estimated in realtime [7].

Local force feedback is posed to combine the benefits of both approaches: hiding slave dynamic forces and increasing contact sensitivity while maintaining overall loop stability properties. In this work, we assume a master-slave connection via a passive controller and focus our attention on the local force regulation. In particular, we address the application to a high-inertia, high-friction, non-backdrivable industrial slave robot. Unlike many teleoperator robots which are impedance controlled [8], this industrial robot reads in position commands and effectively

*Address all correspondence to this author.

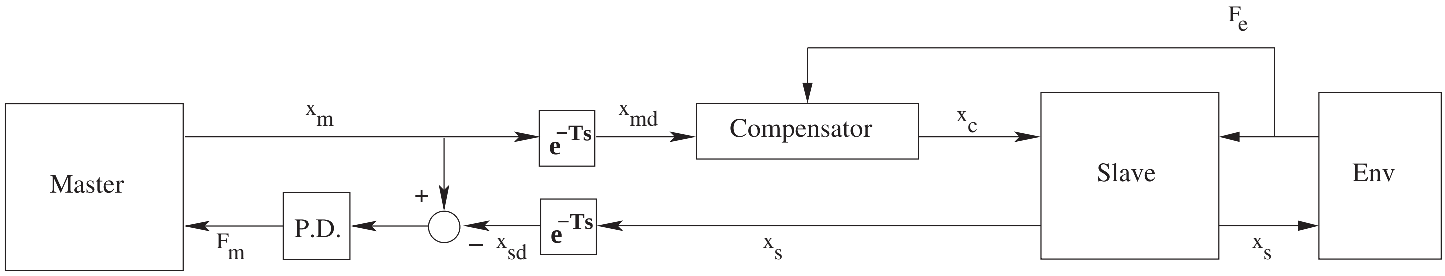


Figure 1. TELEROBOTIC ARCHITECTURE FOR AN ADMITTANCE SLAVE ROBOT WITH LOCAL FORCE FEEDBACK

acts as an admittance device. A local controller is presented which converts the slave into an apparent impedance device. Experiments demonstrate that the slave is thereby compatible for a passive telerobotic architecture with appropriate forces felt by a user.

## TELEOPERATOR WITH LOCAL FORCE FEEDBACK

Figure 1 depicts the overall system structure, including a local force feedback loop at the slave site. The master robot represents an impedance device displaying a force $F_m$ while reading its position $x_m$. In contrast, we assume the slave robot functions as an admittance device following position commands $x_c$ and measuring environment forces $F_e$. Thus, the overall setup operates as an impedance-admittance teleoperation system [9].

As both master position $x_m$ and slave position $x_s$ are transmitted through a communications channel, they may experience some delay $T$, with $x_{md}$ and $x_{sd}$ indicating the potentially delayed positions respectively.

The master, as an impedance device, is controlled with a proportional-derivative (P.D.) controller, which makes the force displayed and felt by the user dependent on the master-slave tracking error. We naturally want this force to reflect any contact force experienced by the slave, so that the system can operate as transparently as possible. Herein also lies the fundamental challenge of the architecture and impedance devices: that the external force information is encoded in the tracking error. As such, we require the slave to be backdrivable and change position based on contact. Meanwhile without contact, if the slave robot is in free space, we desire a zero tracking error so the user feels no forces.

To make our assumed non-backdrivable slave respond to contacts, we include the local force feedback loop, as seen in figure 1. The environment force $F_e$ as measured by a sensor, is used to adjust the slave's motion. This both decreases the contact deflection, lowering contact forces and protecting the robot and environment, and introduces a tracking error which the user can feel.

For the purposes of this paper, we focus our attention on implementing the local feedback and examining to what extent the tracking error contains contact information. In effect, we examine whether a physically non-backdrivable slave can operate in a back-driven fashion. Closed loop stability, which depends on the master dynamics and the transmission delay in addition to the slave tracking is not addressed explicitly. Instead we intend to use standard passivity-based architectures designed for a back-drivable slave.

We use an experimental setup, as presented in figure 2. The master robot is a PHANToM haptic device capable of updating

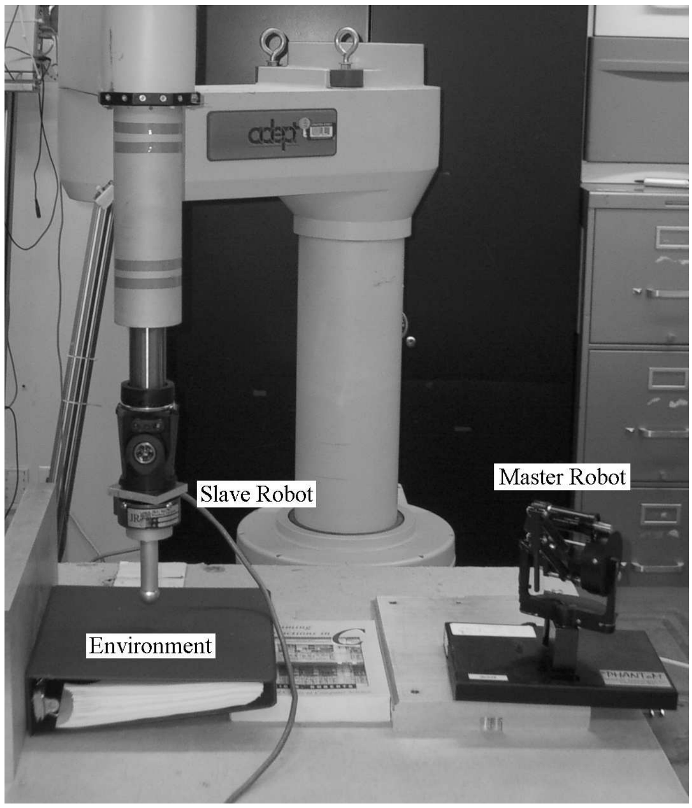


Figure 2. EXPERIMENTAL SETUP

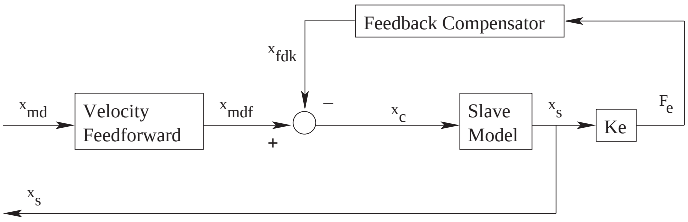


Figure 3. SLAVE COMPENSATION STRUCTURE

forces and measuring positions on a master computer in realtime at a rate of 1 kHz. The PHANToM has low inertial and frictional properties and is thus suited well as a master teleoperator device [10]. The slave is an AdeptOne 5-axis Scara industrial robot (see *Teleoperated System* in [11]). It has high frictional and inertial properties and is not backdrivable. The Adept is able to receive position commands at a rate of 62.5 Hz from a slave computer which also reads the contact force sensor. Communications between the master and slave are achieved through a network using the TCP protocol.

## SLAVE COMPENSATION

Figure 3 shows the designed slave compensation architecture including local force feedback. The delayed master position $x_{md}$ is fed through a velocity feedforward block producing a master position delayed feedforward $x_{mdf}$. The environment force $F_e$ is fed through a feedback compensator and subtracted from $x_{mdf}$ to produce a commanded slave position, $x_c$.

### Slave Model

To properly tune the force feedback compensation, we need a model of the slave dynamics, in this case, relating the commanded position $x_c$ to the actual position $x_s$. We assume the measured position correlates well with the tip position such that the environment sees the same motions. In particular, we used system identification tools to analyze open loop step responses. These fit a 2nd order model with a pure time delay:

$$\frac{x_s(s)}{x_c(s)} = \frac{50s+600}{s^2+50s+600} * e^{-0.033*s} \tag{1}$$

The Adept has an internal controller that computes smooth position trajectories, which dominates these dynamics and imposes the delay. This delay adds significant phase and can cause instabilities at high frequencies. Overall closed loop bandwidth was limited to approximately 20 rad/s or 3 Hz because of this delay.

### Velocity Feedforward

Adept's internal controller accepts only position commands, while we assume that velocity commands are also available from the master. To improve tracking and incorporate velocity commands, we update the command position to

$$x_c = x_{md} + T_{ffw} * \dot{x_d} \tag{2}$$

where $T_{ffw}$ should match the time constant of the Adept controller. Indeed compare a standard controller with velocity commands

$$F_d = K_p(x_c - x) + K_v(\dot{x_c} - \dot{x}) \tag{3}$$

to the same controller without velocity commands

$$F_d = K_p(x_c - x) + K_v(0 - \dot{x}) \tag{4}$$

to motivate this velocity feedforward.

This adjustment means the Adept now receives the same info as typical controllers and can respond faster to desired motions. To limit noise this adjustment might inject, we further elect to filter the velocity signal at time constant $\tau$

$$x_c = x_{md} + \frac{T_{ffw}}{1+\tau s} * \dot{x_{md}} \tag{5}$$

which in the Laplace domain takes the from

$$\frac{x_c(s)}{x_{md}(s)} = 1 + \frac{T_{ffw}s}{1+\tau s} = \frac{1+(T_{ffw}+\tau)s}{1+\tau s} \tag{6}$$

In effect, the velocity feedforward compensator is a lead compensator.

In our application, we tuned the Velocity Feedforward compensator as

$$\frac{x_{mdf}(s)}{x_{md}(s)} = 5 * \frac{s+125}{s+625} = \frac{1+0.008s}{1+0.0016s} \tag{7}$$

### Feedback Compensator

The feedback compensator provides the local force feedback. It was tuned against a slave environment of approximately $K_e$ = 10 N/mm. In consideration of the slave model (1) a lead/lag structure was chosen for the compensator

$$\frac{x_{fdk}(s)}{F_e(s)} = K_{fc} * \frac{(s+z_{lead})(s+z_{lag})}{(s+p_{lead})(s+p_{lag})} \tag{8}$$

 

| | Environment | Architecture |
|---|---|---|
| Case 1 | Freespace | No Local Force Feedback |
| Case 2 | Freespace | Local Force Feedback |
| Case 3 | Contact | No Local Force Feedback |
| Case 4 | Contact | Local Force Feedback |

Table 1. Experiment Cases

The lag enhances low frequency steady state behavior, while the lead extends the loop's bandwidth.

After tuning the Feedback Compensator in the experimental setup, the compensator took the form

$$\frac{x_{fdk}(s)}{F_e(s)} = 0.08322 * \frac{s^2+140.6s+211.1}{s^2+179.9s+157.7} \tag{9}$$

## EXPERIMENT

Four cases were conducted to evaluate the ability of local force feedback to enhance operation and feedback to the user (table 1). In cases 1 and 2 the motion stayed above any contact. In cases 3 and 4 the motion twice made contact with the environment allowing application of contact forces. These tests were performed with and without local force feedback, such that cases 1 and 3 ignored the compensation and used

$$x_c = x_{mdf} \tag{10}$$

Meanwhile cases 2 and 4 enabled the local force feedback

$$x_c = x_{mdf} - x_{fdk} \tag{11}$$

### Set Up

To isolate the slave performance and provide a repeatable test, the motions of the PHANToM master were recorded and reused in related tests. Two sets of PHANToM position data were collected and stored, one set of master motions in freespace only, which was used in cases 1 and 2 and another set of master motions in freespace and contact used for cases 3 and 4. For both sets of data, the starting PHANToM position was 27mm above the environment.

Master position, slave position, environment force, and effective force data was collected for analysis. Master and slave position was read in from the PHANToM and Adept robots respectively, while environment forces were measured from a force sensor on the end-effector of the Adept robot.

An effective feedback force that would be displayed to the user was computed as

$$F_{fdk} = K_{phan} * (x_s - x_{md}) \tag{12}$$

where $K_{phan}$ is a stiffness gain applied at the PHANToM master to produce a force on the user based on the difference between master and slave positions. $K_{phan}$ was set to the slave stiffness in steady state, thus the master and slave stiffnesses were effectively equal

$$K_{phan} = \frac{F_e}{x_{md} - x_s} (SteadyState) \tag{13}$$

$$K_{master} = K_{slave} \tag{14}$$

Using figure 3 and (9, 13), $K_{phan}$ was determined to be 8.98 N/mm.

In a full closed-loop situation the value of $K_{phan}$ will be limited by stability considerations, in particular by communications delay and the master dynamics. For zero delay a PHANToM's typical maximum gain is 10 N/mm.

### Results and Analysis

Figure 4 shows the experimental results for cases 1-4. The left column shows how closely the slave position $x_s$ was able to track the master desired position $x_{md}$ for each of the cases. A dotted line at -27mm marks the position of the environment. In the right column, measured environment forces $F_e$ are compared with the calculated effective forces $F_{fdk}$.

In freespace the slave position $x_s$ was able to track the master desired position $x_{md}$ closely for cases 1 and 2. Note that the slave position does not significantly lag the master desired position even though the slave model contains a pure time delay of 33ms. This is because the velocity feedforward is able to compensate for this delay by effectively predicting future positions based on previous filtered positions and works as long as the user operates at a bandwidth of around 3Hz or less. The measured environment forces $F_e$ were zero for cases 1 and 2 since motion only occurred in freespace. Tracking in freespace wasn't exact and so there was some effective feedback force.

At times of about 2sec and 5.5sec, the slave exhibited sharp changes in velocity, which resulted in large effective feedback forces. These drastic changes were likely due to a sleep timer going off in the real-time operating system, since the master desired position $x_{md}$ did not contain these spikes.

Cases 3 and 4 show the benefit and effect of local force feedback. In case 3 without local force feedback, the slave was able

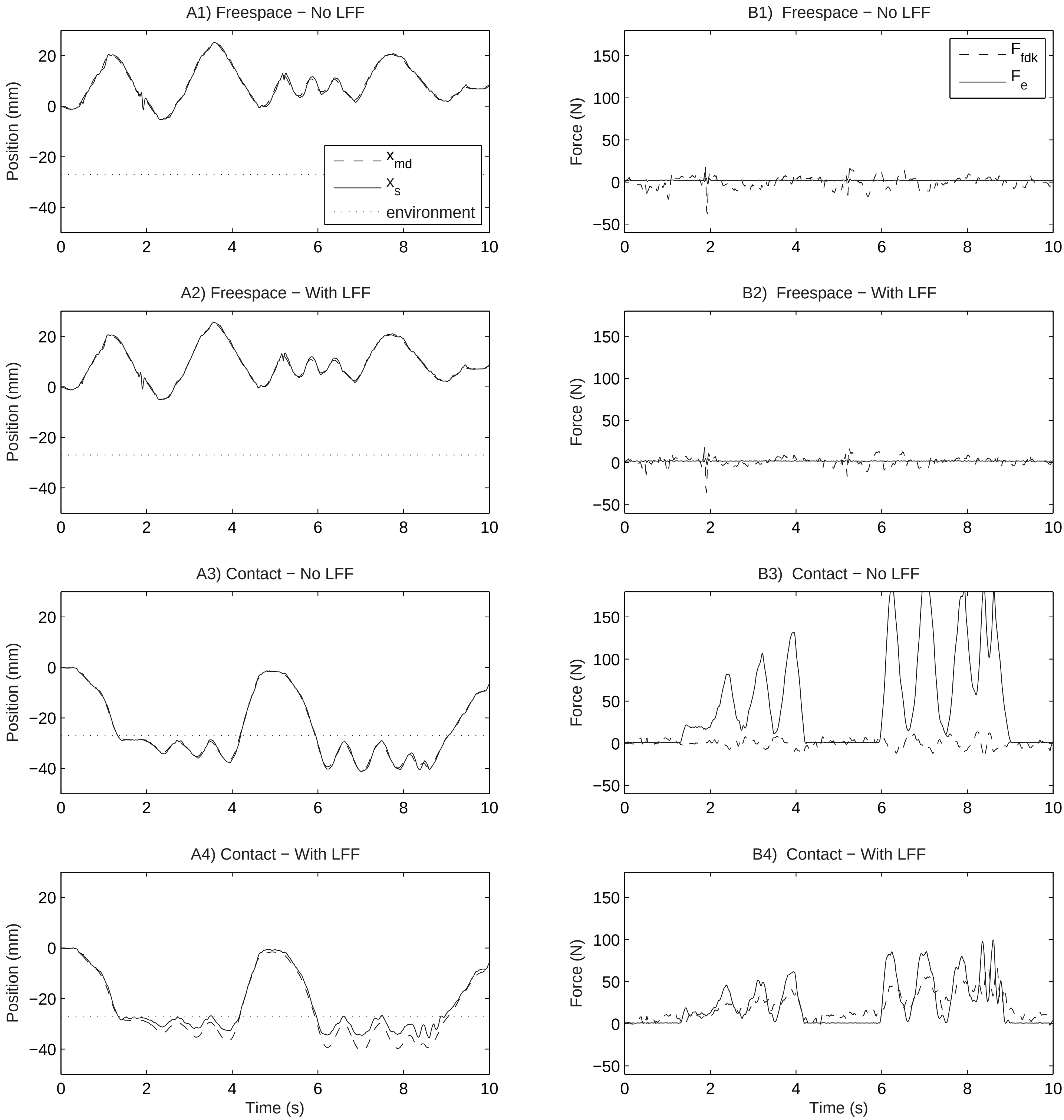


Figure 4. EXPERIMENTAL RESULTS WITH AND WITHOUT LOCAL FORCE FEEDBACK (LFF)

to track the master closely in freespace and in contact. Indeed the slave is non-backdrivable and forces its way into the environment. Without appreciable tracking error, the effective force was negligible even while the slave was experiencing large environment forces $F_e$. The controller was insensitive to the environment and thus the user would never feel any environment contact forces.

In case 4 with local force feedback, the slave closely followed the master position while in freespace but diverged when in contact with the environment. This position difference was due to the feedback compensator and created significant effective forces. At the same time, the adjusted slave position commands also lowered the environment force. If desired, $K_{phan}$ could have been adjusted so that $F_{fdk}$ matched $F_e$ allowing the user to feel the same forces as the slave. However, this would cause the master and slave stiffnesses to no longer be equal.

The current telerobotic system is limited primarily by the shortcomings of the slave Adept robot. Adept's internal time delay makes it difficult to maintain a stable system. This further confines the user to operate below 2-3Hz, as faster motions lead to significant tracking errors, which in turn the user experiences as dynamic forces.

More direct control over Adept's internal desired position will substantially improve user bandwidth and free space tracking errors.

## CONCLUSION

This work has shown that local force feedback can allow a user to feel environment forces that would otherwise be hidden by the non-backdrivable nature of the slave robot. If an appropriate position gain can be applied at the master, the user will experience a force approximately equal to the contact force, creating a haptic sense of the environment. A non-backdrivable admittance device is thus converted into a backdrivable impedance behavior.

As a further advantage, this approach enables the application of many existing impedance-based teleoperation controllers. Avoiding the direct transmission of force sensor feedback to the user, this strategy can even be used in conjunction with passive controllers that can accommodate substantial communications delays.

While the Adept robot's internal controller imposes substantial limits on the tracking response and bounds the bandwidth to a few Hertz, users do not usually exceed these frequencies. Nevertheless, in the future using this approach on slave robots with direct access, we hope to demonstrate a substantial reduction in dynamic forces experienced by the user. As such, we hope to widen the possibilities for teleoperation to utilize high-precision slave devices not originally intended for human-in-the-loop control.

## ACKNOWLEDGMENT

This work was supported by the National Aeronautics and Space Administration via the Institute for Space Robotics.

## REFERENCES

[1] Niemeyer, G., and Slotine, J.-J. E., 1991. "Stable adaptive teleoperation". *IEEE Journal of Oceanic Engineering,* **16**(1), Jan., pp. 152–162.

[2] Niemeyer, G., and Slotine, J.-J. E., 2004. "Telemanipulation with time delays". *Int. Journal of Robotics Research,* **23**(9), Sept., pp. 873–890.

[3] Lawrence, D. A., 1993. "Stability and transparency in bilateral teleoperation". *IEEE Transactions on Robotics and Automation,* **9**(5), Oct., pp. 624–637.

[4] Hashtrudi-Zaad, K., and Salcudean, S. E., 2002. "Transparency in time delayed systems and the effect of local force feedback for transparent teleoperation". *IEEE Transactions on Robotics and Automation,* **18**(1), Feb., pp. 108–114.

[5] Arcara, P., and Melchiorri, C., 2002. "Control schemes for teleoperation with time delay: A comparative study". *Robotics and Autonomous Systems*(38), pp. 49–64.

[6] Daniel, R. W., and McAree, P. R., 1998. "Fundamental limits of performance for force reflecting teleoperation". *Int. Journal of Robotics Research,* **17**(8), Aug., pp. 811–830.

[7] Park, J., and Khatib, O., 2006. "A haptic teleoperation approach based on contact force control". *Int. Journal of Robotics Research,* **25**(5-6), May, pp. 575–591.

[8] Hannaford, B., 1989. "A design framework for teleoperators with kinesthetic feedback.". *IEEE Transactions on Robotics and Automation,* **5**(4), Aug., pp. 426–34.

[9] Hashtrudi-Zaad, K., and Salcudean, S. E., 2001. "Analysis of control architectures for teleoperation systems with impedance/admittance master and slave manipulators". *The International Journal of Robotics Research,* **20**(6), June, pp. 419–445.

[10] Cavusoglu, M. C., Feygin, D., and Tendick, F., 2002. "A critical study of the mechanical and electrical properties of the phantom hatpic interface and improvements for high-performance control". *Presence,* **11**(6), pp. 555–568.

[11] Shull, P. B., and Gonzalez, R. V., 2006. "Real-time haptic-teleoperated robotic system for motor control analysis". *Journal of Neuroscience Methods,* **151**(2), Mar., pp. 194–199.