Human-Machine Admittance and Transparency Adaptation in Passive User Interaction with a Haptic Interface

Samuel T. McJunkin* Yanfang Li* Marcia K. O'Malley*
(*)Rice University, Houston, TX, USA
E-mail: smcj@rice.edu, yvonneli@rice.edu, omalleym@rice.edu

Abstract

This paper addresses human adaptation to changes in coupling impedance and force amplitude during passive user induced (PUI) interactions with a haptic interface. PUI interactions are characterized as event-based haptic interactions or haptic recordings that are replayed to the user. In the study, virtual environments are displayed to passive users with variable coupling stiffness and force amplitudes, and transparency bandwidth and human-machine admittance are measured. Results indicate that transparency bandwidth and the human-machine admittance do not change significantly for permutations of force amplitudes and coupling impedances, nor do they vary significantly across users. The reason for this invariance is that, during a PUI interaction, users tend approach a similar displacement profile. As a result, all users will have similar apparent admittance and transparency. The findings give sufficient justification for the use of universal compensators that improve transparency bandwidth, and that can be designed based solely on a priori transparency measurements for a typical user.

1. Introduction

Haptic interfaces are a class of robots with which humans interact to give the sensation of an object or an environment that is simulated or transmitted remotely by a slave manipulator. In many cases, these manipulators have a closed dynamic loop in which the manipulator is grounded and the human, who becomes a part of the system, is also grounded. Figure 1 shows this concept for an impedance-based manipulator. From Figure 1, it is easy to see how the manipulator transmits forces to simulate the interaction with an environment.

Haptic interfaces generally have two modes of operation: active user interactions (AUI) and passive user interactions (PUI). Haptic interactions are typically of the AUI variety; this is because the AUI is based upon interaction with environmental impedances, which is intuitive from a physical modeling perspective. For example, virtual walls are modeled as stiff springs in parallel with mechanical dampers. Figure 2 shows an example of an interaction with a spring environment where X_H denotes the displacement of the user. In this scenario, user motion (X_H) is measured, and resultant forces due to deflection of the virtual springs are displayed via the haptic device.

While the AUI approach to simulation display is the most common for haptic displays, the approach is not always a desirable means of displaying an environment. Limitations in hardware such as zero-order hold problems [1] can lead to instability when rendering rigid surfaces as high-stiffness virtual springs in parallel with virtual dampers. To compensate for these limitations, surfaces are modeled with smaller stiffness and damping coefficients to ensure stability. In turn, this leads to lower fidelity simulations, since rigid contacts are modeled with more compliant elements.

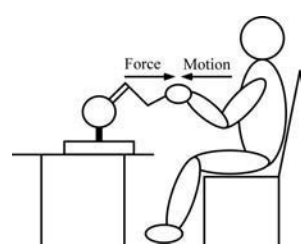

Fig. 1. Human interaction with an impedance-based haptic interface

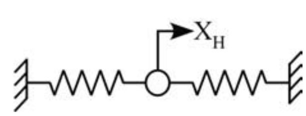

Fig. 2. Active user interaction with a spring environment on X-Axis

1.1. Event-Based Haptics

An alternative to the traditional AUI display is to display a force profile that is not directly coupled to

Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems
0-7695-2310-2/05 $20.00 © 2005 **IEEE**

the user's displacement. This approach assumes that the human operator is passive, and the force is displayed to the user for interpretation. For example, a user may come in contact with an object in the virtual environment that is not defined as an impedance alone; instead, it may be a vibration that is used to convey texture or provide a cue to the user. It may also be an object defined by an impedance and an active force; Figure 3 shows such an example where F_C is the commanded force. In the PUI haptic display pictured, a human user feels the force command F_c, which is independent of their position in the virtual environment. In addition, the user feels a force dependent on the positional interaction with the virtual springs.

PUI interactions have been realized in two cases in the literature. First, Hwang et al implemented an event-based PUI simulation of tapping on rigid surfaces [2]. Position information from the haptic device is used in a force generation algorithm, although the force itself is not dependent on the position of the end effector. Similarly, Okamura et al [3] use PUI methods to display forces to a user during cutting of simulated tissue. In these cases, realistic force displays are difficult to achieve through impedance based models, and high frequency force information inherent in rigid surface tapping is important in order to maintain sufficient simulation fidelity.

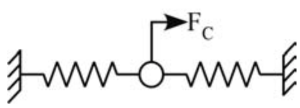

Fig. 3. Passive user interaction with a spring environment on the X-Axis

1.2. Transparency as a Performance Measure

One goal of any haptic simulation is to maintain transparency for a sufficiently large bandwidth. Transparency is defined as the ratio between transmitted and simulated impedance [4] where the ideal ratio is unity for a desired bandwidth. For the purposes of this paper, bandwidth is defined as the ±3dB crossover frequency from 0dB for the transparency transfer function, which is the ratio defined above. A transparent haptic system enables a user to feel the virtual environment without sensation of manipulator dynamics. Moreover, the transparency bandwidth should be greater than the bandwidth of the displayed environment. Transparency shows how effectively a manipulator displays an environment; changes in transparency would reflect the need for compensators that adapt to those change. The following sections describe the relevant literature for transparency as a performance measure in teleoperation and haptic systems and the methods used to improve performance.

1.2.1. Transparency in Teleoperation. Transparency and stability are of critical importance in teleoperation systems. It is the goal of teleoperated systems to first be stable, and second be transparent in the desired frequency range. Teleoperated systems face unique challenges related to communication lag, unknown human interaction forces, and the fact that their environment is not always well characterized. In short, the teleoperation system is generally a nonlinear, time variant system. Given that this is the case, attempts have been made with some success to characterize and control these unknowns to obtain stability and extended transparency bandwidth. Most attempts to date characterize the teleoperation system as a linear system. In such cases, the environment and human dynamics and time lag are combined as disturbances or are linearized for analysis. As such, most of the techniques used to improve stability rely on compensators of some type. Linear compensators of the lead-lag type have been shown to extend transparency bandwidth in simulation [5]. Other compensators use adaptive control laws to optimize for a given performance criteria, usually transparency or stability [6, 7]. In addition, it has been observed that unity transparency between the remote and the transmitted environment impedances is not always desirable [8]; Colgate observes that indeed it may be desirable to shape impedances to achieve stability and transmit impedances that are more meaningful to the user. Cases would include magnifying impedances in micro scale teleoperation or minimizing impedances in macro scale teleoperation.

1.2.2. Transparency in Virtual Environments. Transparency in virtual environments is merely a special case of teleoperation. In virtual environments, the goals are similar to that of teleoperation: maintain display stability and sufficient transparency bandwidth. In these simulations, the approach to improve transparency and stability characteristics has been either with closed loop feedback [9] or open loop linear compensators [10]. Eom et al. have taken an approach to examine stability and transparency from a non-linear perspective where a disturbance observer is included in the haptic loop, and use Lyapunov stability criteria to verify stability [11]. This is a step closer to actually examining the general haptic interface, which is typically nonlinear in its kinematics, and therefore, dynamics.

1.3 Human Admittance

During a PUI interaction, the dynamics of the human operator may change, in turn affecting the dynamics of the simulation and possibly the way the human perceives the simulated environment. These dynamics are the human-machine admittance. Hogan [12] notes that robotic manipulators are an admittance along with the environment they interact with; in this case, the manipulator is the haptic device and the human is the environment. It is difficult to decouple the human and the machine in terms of their admittance, and so for convenience, they are viewed together.

Fite and colleagues [5] do not make this distinction when incorporating the admittance of the user in a teleoperation interaction; this is a simplifying assumption that the manipulator admittance is insignificant when compared to the human admittance. In contrast, the human-machine admittance is mentioned here for completeness. The machine admittance is fixed but human admittance is certainly variable since changes in muscle contraction, grip, and posture may result in changes in admittance. Therefore, any changes in the human-machine admittance are due to the human, not the machine. In this study, this measure is quantified for PUI interactions as a means of determining how the users adapt to changes in a PUI interaction.

2. Problem Definition

The transparency bandwidth of the Phantom 1.0A haptic interface (SensAble Technologies, Woburn, MA) and the human admittance are measured for passive user-induced (PUI) interactions with the haptic interface. These tests evaluate how different users, force amplitudes, and environmental impedances affect transparency bandwidth and human admittance for a given frequency bandwidth for specific interaction types. Figure 4 shows the block diagram for a PUI haptic simulation where X_H is the human displacement, Z_E is the environment impedance, F_C is the commanded force, F_D is the desired force, and F_M is the measured force. Y_{HM} represents the admittance of the manipulator and the human linked together.

G_T represents the transparency transfer function, defined earlier as the ratio of transmitted to simulated impedance. Transparency is defined as in Equation 1 using the ratio of measured force to the desired force from the block diagram.

$$G_T = \frac{F_M}{F_C - X_H Z_E} \tag{1}$$

Similarly, the human-machine admittance is a calculated measure defined in Equation 2.

$$Y_{HM} = \frac{X_H}{F_M} \tag{2}$$

These quantities will be measured experimentally and compared for varying conditions.

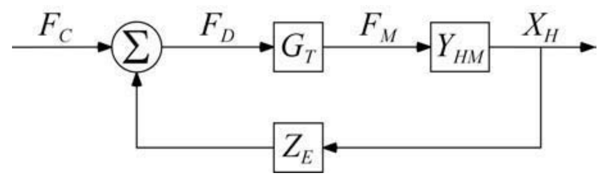

Fig. 4. Block diagram of haptic interaction actively displaying force while user is a passive element

3. Experimental Procedure

Five right-handed subjects, ages 23 to 27, held the stylus of the Phantom 1.0A in a PUI interaction. The subjects were instructed to not rest their elbow but hold the stylus in such a way that the shoulder was the mechanical ground point for the user. In each trial, a force chirp was displayed through a spring environment and was applied directly as in Figure 3.

The desired force amplitude ranged from 2 to 6 N at intervals of 2 N and the spring stiffness ranged from 0 to 100 N/m at intervals of 50 N/m. During a given trial, the subject gripped the stylus and remained passive as forces were displayed. In addition, the user was not provided any visual cues as the manipulator moved; the user simply maintained his/her grip. The length of the force chirp was 25 seconds with a linear ramp that ended at 50 Hz; the force-sampling rate was 200 Hz with a haptic thread update rate of 1000 Hz. Subjects completed five trials for each value of force and stiffness.

Figure 5 illustrates the coordinate frame assigned to the Phantom 1.0A for the purposes of discussion. The X direction is used to define motion parallel to the human operator and the floor, the Y direction represents motion normal to the floor and parallel to the operator, and the Z direction corresponds to motion normal to the operator and parallel to the floor. During the trials, motion is constrained to the X axis.

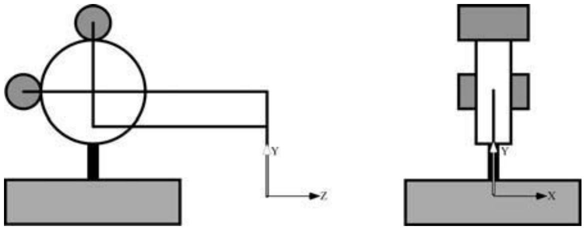

Fig. 5. Phantom Premium with orientation axis in world frame

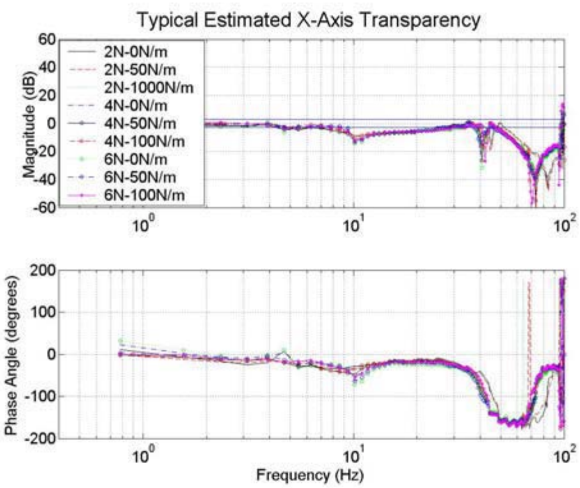

Fig. 6. Transparency for a typical subject over range of operating conditions

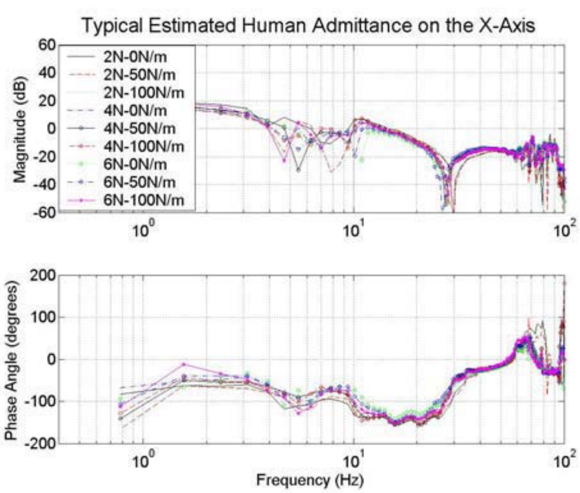

Fig. 7. Transparency for all subjects at typical operating condition

During each trial, the virtual environment impedance (Z_E) is known, along with the commanded force F_C. Encoders on the Phantom allow for measurement of X_H, the user's position. An ATI Nano17 six-axis force sensor was mounted on the last link of the Phantom 1.0A in order to measure F_M. From these values, we are able to calculate G_T and Y_{HM} according to equations 1 and 2.

To clarify, the PUI interaction in this study asks the user to determine information about an environment that transmitted to them without probing an impedance. This is the event in "event-based" haptics for this particular case. In these experiments, subjects are asked to simply maintain a grip and allow the manipulator to move them; the playback is purely temporal.

4. Results

Five subjects were subjected to a range of input force amplitudes (2 to 6 N) and coupling impedances (0 to 100 N/m) for PUI interaction with a compliant environment with an overlaid sinusoidal force sweep. Results for transparency and human admittance are presented in the following sections.

4.1. Transparency

Figure 6 shows transparency data, averaged over five trials, for a typical subject for all combinations of force amplitude and environment impedance. Note that there is not significant deviation from case to case. Figure 7 shows average results over five trails for each subject at one force-stiffness combination. Again, note the similarity in transparency measures for all subjects.

4.2. Human-Machine Admittance

Figure 8 shows human admittance results averaged over five trials for all combinations of force amplitude and environment stiffness for a single representative subject. Except at frequencies of 5 to 10 Hz, there is not a significant deviation from case to case. Figure 9 shows human admittance measurements, averaged over five trials, for all subjects for a single force amplitude-stiffness combination. This plot illustrates the invariance admittance from user to user and case to case.

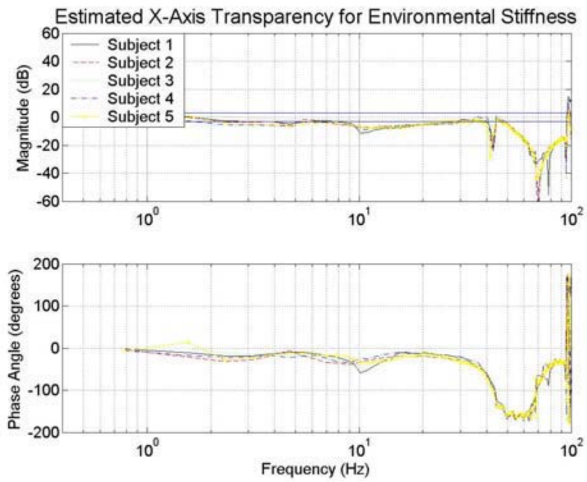

Fig. 8. Admittance for a typical subject over range of operating conditions

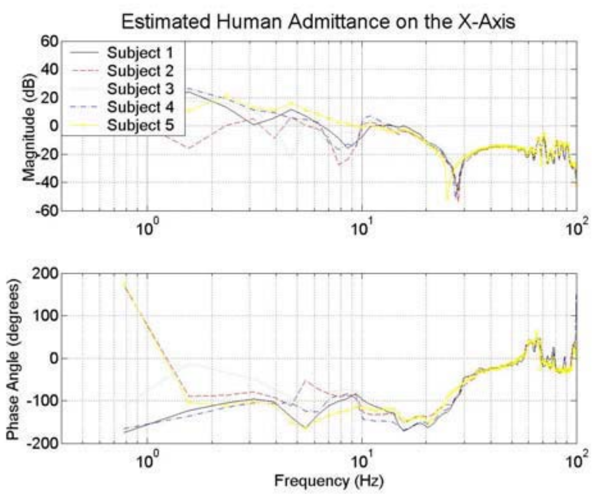

Fig. 9. Admittance for all subjects at typical operating condition

5. Discussion

The following sections present a discussion of results from the transparency and admittance measurements, and present the implications of these findings.

5.1. Transparency and Human-Machine Admittance

Figures 6 through 9 show that users generally are invariant in terms of the mechanical properties measured, specifically transparency and human admittance.

For a particular operating point (F_C-Z_E combination), this is consistent from the standpoint of a linear transparency transfer function estimate, which should not change from user to user; in fact, it should remain consistent since transparency is a function of the manipulator dynamics and simulation algorithms, not the users, for the PUI interaction.

The calculated admittance is the human-manipulator admittance since the two cannot really be separated since neither is well characterized. However, it is reasonable to assume that the manipulator admittance is invariant, and so, it is assumed that if the human-manipulator admittance changes, it is due to the human admittance.

5.2. Transparency and Admittance Invariance

From the definition of transparency and the human-manipulator admittance, it would seem that there should be significant deviation for different users and different operating conditions; one must ask the question why there is no deviation. The answer is found in the nature of the PUI interaction and the bounds of the manipulator to display impedances and forces.

In active user-induced interactions, results show that the estimated transparency transfer function bandwidth ranges from 2-5 Hz and is about 2 Hz when averaged over all subjects [13]. In this work, displacement as function of frequency was also examined, with the displacement amplitude dropping below -50 dB between 2 to 4 Hz. This observation corresponds to the transparency bandwidth of the active tests. Analysis of transparency using simulation rather than experiments relying on the human for excitation shows that if excitation at higher frequencies were sufficient, the manipulator would have a transparency bandwidth of 11 Hz, which far exceeds the apparent excitation, range of the user. Therefore, the actual transparency of the system is independent of the user in an AUI interaction and only depends on the ability of the manipulator to display a given environment.

From a system definition perspective, a perfectly transparent manipulator is one that is able to transmit simulation forces through the manipulator without the dynamics of the manipulator or uses an algorithm that corrects for the manipulator dynamics. In the PUI case, the manipulator was used to generate displacements rather than the human users. This displacement profile is invariant from user to user and condition to condition as seen in Figure 10.

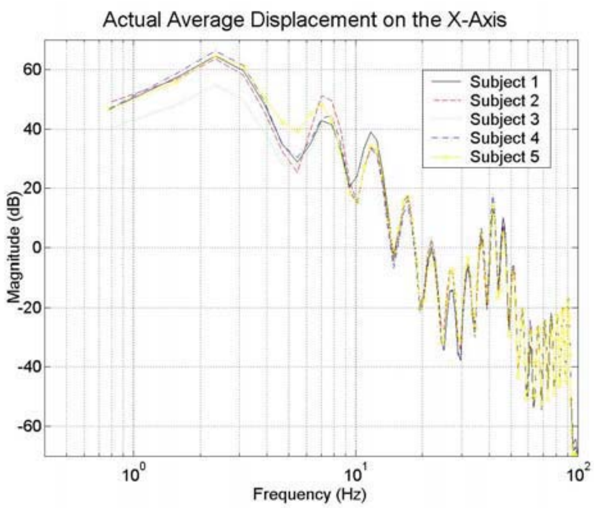

Fig. 10. Displacement profile for all subjects at a particular operating condition

Since this displacement amplitude was consistent, the conditions for transparency were also the same from the system perspective. The forces measured by deflection of the load cell were similar for all subjects. This is important to note since the load cell certainly does not measure the acceleration of the manipulator and the human, which undoubtedly should be considered in the measure of transmitted force. However, if these accelerations or dynamic elements are small, these can safely be viewed as insignificant. At higher frequencies this is no longer the case.

Human admittance does not vary over any of these cases; the reason behind this can be deduced from the displacement plots. The invariance of the displacement data shows that the users were displaced in an identical fashion and leads to the conclusion of invariant admittance. One must be careful to note however that this is unique in this instance only and cannot generalized, as most human-manipulator PUI interactions happen within a subspace of the entire space defining the human-machine admittance and operating conditions.

Consider for the moment, two extremes from the perspective of a user: a low force display and a high force display. The low force display will see most users as a fixed body, since the output of the display is below the maximum force output capabilities of a human operator. As a result, the smallest user has an admittance that is below the bound of what the manipulator can effectively move. The force of this manipulator is so small that the user completely arrests it regardless of their size, build, or strength. The high force display, on the other hand, would treat a user as a minor inertial error effectively moving the user about regardless of their low admittance. In the limiting cases, we see how the user can, or cannot, effectively determine the nature of human-machine interactions. Thus, these limiting cases clarify how most PUI interactions occur within a subspace human-machine admittance and operating conditions. In the context of these data, these interactions fall into the category of a low force display; most displays fall into this category since the user dynamics dampen velocity.

5.3. Apparent Fidelity

The transparency measurement presented here does not address how the force is perceived qualitatively; the only way to quantitatively measure this would be to measure force profiles during a real task, such as tapping on a surface, and its simulated task and then examining the ratio of the two over a given bandwidth. This type of experimental measure would allow for a quantitative measure of a simulation quality by comparing the real interaction with the simulated one.

5.4. Universal Compensators

Transparency and human-machine admittance measurements, as quantitative tools, provide some useful extensions for design of compensators to improve performance of haptic displays. The lack of significant adaptation on the part of the user shows that the human being can be considered constant in reference to their admittance. This is significant because prior research by Kuchenbecker et al [14] and Speich et al [15] show that there are non-trivial differences between users in terms of dynamics when interacting with haptic displays. The findings of this paper do not contradict that research, but rather, augment their findings by suggesting that these differences, while significant when viewed alone, fall below the bound of what makes a difference in terms of what the manipulator can display. With this conclusion, it is now possible to design open loop compensators that improve measured transparency similar to the work of Fite et al [5], Speich et al [16], and Colgate [8], without having to consider variations between users or different operation conditions. It is sufficient to design a generalized compensator that corrects transparency for a typical case, since variations in user admittance and transparency measures are minor. It should be noted that these results are unique for a given manipulator, and implementation of open loop or closed loop control methods for improving transparency bandwidth must consider the dynamics of the particular haptic display.

However, these data show that it is possible to define a lower bound on what a haptic or teleoperator system should be able to output such that the manipulator does not have to be reconfigured for each user.

6. Conclusions

This work seeks to determine the effect that permutations of coupling impedance and force amplitude have on transparency and the human-machine admittance during a passive user-induced (PUI) interaction.

Results show that transparency and the human-machine admittance are not significantly sensitive to these changes for a low force display. Transparency is found to be a characteristic of a manipulator, without dependence on the dynamics of the human operator. The invariance of the human-machine admittance, however, reflects that most haptic interactions occur within a subset of possible interactions that a human could encounter. Specifically, the forces transmitted in these experiments are small enough that the admittance of the users studied was outside the bound of admittances that the manipulator could move.

Results indicate that it is possible to develop controllers to improve measured transparency for a given haptic interface. The controllers, typically implemented in the form of open-loop compensators, may be designed without concern for the variety of users that may interact with the device, and regardless of the dynamics of the simulated environment to be displayed.

Acknowledgements

The authors gratefully acknowledge NASA grant numbers NAG 9-1538 and NNJ04JF84H.

References

[1] J.E. Colgate and J.M. Brown, "Factors Affecting the Z-Width of a Haptic Display", IEEE International Conf on Robotics and Automation, 1994, pp. 3205-3210.

[2] J.D. Hwang, M.D. Williams, and G. Neimeyer, "Toward Event-Based Haptics: Rendering Contact Using Open-Loop Force Pulses", 12th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 24-31, March 2004, pp. 24-31.

[3] A.M. Okamura, R.J. Webster III, J.T. Nolin, K.W. Johnson, and H. Jafry, "The Haptic Scissors: Cutting in Virtual Environments", Proceedings of the IEEE 2003 International Conference on Robotics and Automation, September 2003, pp. 828-833.

[4] D.A. Lawrence, "Stability and Transparency in Bilateral Teleoperation", IEEE Transactions on Robotics and Automation, October 1993, pp. 9(5):624-637.

[5] K.B. Fite, J.E. Speich, and M. Goldfarb, "Transparency and Stability Robustness in Two-Channel Bilateral Teleoperation", Journal of Dynamic Systems, Measurement, and Control, Sep 2001, pp. 123: 400-407.

[6] H.K. Lee and M.J. Chung, "Adaptive Controller of a Master-Slave System for Transparent Teleoperation", Journal of Robotic Systems, 1998, pp. 15(8):465-475.

[7] K. Hashtrudi-Zaad and S.E. Salcudean, "Analysis of Control Architectures for Teleoperation Systems with Impedance/Admittance Master and Slave Manipulators", The International Journal of Robotic Research, 2001, pp. 20(6):419-445.

[8] J.E. Colgate, "Robust Impedance Shaping Telemanipulation", IEEE Transactions on Robotics and Automation, August 1993, pp. 9(4):374-384.

[9] T. Sirithanapipat, "Haptic Interface Control Design for Performance and Stability Robustness", PhD Disseration, Vanderbilt University, May, 2002.

[10] R.J. Adams and B. Hannaford, "Control Law Design for Haptic Interfaces to Virtual Reality", IEEE Transactions on Control Systems Technology, January, 2002, pp. 10(1):3-13.

[11] K.S. Eom, I.H. Suh, and B.J. Yi, "A Design Method of Haptic Interface Controller Considering Transparency and Robust Stability", Proceedings of the 2000 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2000, pp. 961-966.

[12] N. Hogan, "Impedance Control: An Approach to Manipulation: Part 1-Theory", Journal of Dynamic Systems, Measurement and Control, 1985, pp. 107:1-7.

[13] S.T. McJunkin, M.K. O'Malley, and J.E. Speich, "Transparency of a Phantom Premium Haptic Interface for Active and Passive Human Interaction", ASME Journal of Dynamic Systems, Measurement, and Control, In Review, 2004.

[14] K.J. Kuchenbecker, J.G. Park, and G. Niemeyer, "Characterizing the Human Wrist for Improved Haptic Interaction", Proceedings of IMECE 2003 International Mechanical Engineering Congress and Exposition, November 2003, pp.1-8.

[15] J.E. Speich, L. Shao, and M. Goldfarb, "An Experimental Hand/Arm Model for Human Interaction with a Telemanipulation System", Proceedings of 2001 ASME International Mechanical Engineering Congress and Exposition, November 2001, pp. 1-6.

[16] J.E. Speich and M. Goldfarb, "Implementation of Loop-Shaping Compensation for Multi-Degree of Freedom Macro-Micro Scaled Teleoperation", IEEE Transactions on Control Systems Technology, In Press, 2004.