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Transparency of a Phantom Premium Haptic Interface for Active and Passive Human Interaction

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Abstract— **This paper compares two methods for determining the transparency bandwidth of an impedance based haptic interface with a Phantom 1.0A haptic device. Active user induced (AUI) interaction tests, where the system excitation is generated by a human user, show that transparency bandwidth is limited to approximately 2 Hz. Passive user induced (PUI) interaction tests, where the system excitation is generated by the haptic device with a passive human operator, show that bandwidth can extend up to 50 Hz. Experimental results show that the apparent bandwidth limitations for the AUI interaction tests are dependent on the human user's inability to excite higher frequencies. Consequently, this measurement approach is insufficient for determining system bandwidth of the human operator-haptic interface system. Furthermore, data seem to indicate that there is no appreciable difference in the ability of the Phantom manipulator to display environmental impedances in either AUI or PUI interactions regardless of the user.**

I. INTRODUCTION

A. Haptic Interfaces

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 with a Phantom Premium 1.0A haptic interface (SensAble Technologies, Woburn, MA). From Figure 1, it is easy to see how the manipulator transmits forces to simulate the interaction with an environment.

B. Haptic Interactions

Haptic interactions can be classified into two different types: active user induced (AUI) and passive user induced (PUI) interactions. The AUI case is simply an interaction where the user, as an admittance operator, determines the displacement of the manipulator, as an impedance operator, which interacts with the simulated environment; the environment is simply an impedance and generates a force determined by the displacement vector. The AUI case is easy to visualize. For instance, a user may come in contact with a virtual wall modeled as a spring and a dashpot; as the user attempts to push into the wall, the manipulator senses the position of the physical endpoint and displays a force based on the stiffness and dissipation of the wall. The PUI case is an interaction where the user is purely passive and does not provide a displacement input; the manipulator is an admittance and provides a displacement vector. The second case requires some examples for the sake of clarity. 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; an example might be a rubber ball coming into contact with a virtual paddle that the user is moving in a game of haptic tennis. This type of interaction has been applied to event-based haptic interactions wherein events that are not dependent on the impedance of the environment are displayed when the user spatially interacts with objects that may not be well modeled by impedance methods alone [1]. Regardless, the two classes differ in their respective modes of interaction. In the first, the user actively determines the displacement, velocity, and acceleration of the endpoint while the environment passively responds. In the second case, the environment actively displays force independent of, or co-dependent with, the user's displacement of the endpoint.

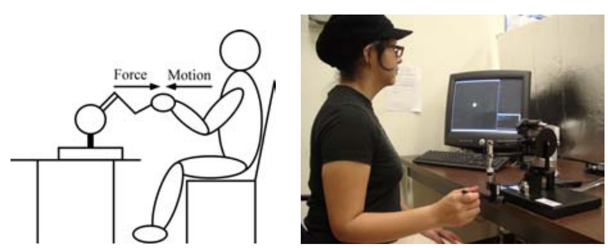

Figure 1: Human interaction with an impedance-based haptic interface

C. Transparency

One goal of any haptic manipulator is to maintain transparency for a sufficiently large bandwidth. Transparency is defined as the ratio between transmitted and simulated impedance [2] where the ideal ratio is unity for a desired bandwidth. The bandwidth is defined as the ±3dB crossover frequency from 0dB for the transparency transfer func-

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tion, which is the ratio defined above. From the user's perspective, a transparent system enables haptic perception of the environment without sensing manipulator dynamics. Moreover, the transparency bandwidth should be greater than the bandwidth of the displayed environment. In this study, transparency measures are quantified for AUI and PUI interactions as a means of determining the possible utility of compensators and human model-based observers.

II. Prior Work

A. Transparency and Stability in Teleoperation

Transparency is 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. Most attempts to date characterize the teleoperation system as a linear system. In such cases, the environment, human, and lag are combined as disturbances or are linearized for analysis. As such, most 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 [3]. Other compensators use adaptive control laws to optimize for a given performance criteria, usually transparency or stability [4, 5]. In addition, it has been observed that unity transparency between the remote and the transmitted environment impedances is not always desirable [6]; 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.

B. 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 increase transparency bandwidth. In these simulations, the approach to increase transparency bandwidth and stability has been either with closed loop feedback [7] or open loop linear compensators [8]. Eom et al. have taken an approach to examine stability from a non-linear perspective where a disturbance observer is included in the haptic loop, and use Lyapunov stability criteria to verify stability [9]. This is a step closer to actually examining the general haptic interface, which is typically nonlinear in its kinematics, and therefore, dynamics.

C. Experimental Results

The results from these prior simulation studies and experiments raise questions regarding the approaches themselves and utility in their implementation. In [7] and [10], transparency bandwidth is only 1 Hz for AUI interactions, which is not sufficient for haptic interactions where 20 to 30 Hz would be desirable. In general, these results seem to be dependent on the human excitation, at least in AUI interactions. If these results are dependent on the fact that the human operator excites a limited frequency band, then one must ask what these compensators are compensating for: the user, the haptic system, or both.

D. Scope of Work

In this work, the measurements initially gathered by Sirithanapipat [7] using a custom built haptic interface are reproduced using a Phantom 1.0A, specifically, AUI interactions with a simulated environment and PUI interactions where the manipulator produces a force through a simulated environment. These results show that in AUI interactions the user, not the manipulator, is the source of apparent limited transparency bandwidth. Moreover, the PUI interaction experiments presented here illustrate that the user minimally affects transmitted impedance.

In addition, the implications of this work cover a variety of areas of interest within the haptics community, specifically in relation to man/machine interfaces. First, a static force equilibrium must exist at the man/machine interface as a consequence of a kinematically static human grip at the interface. Second, previous work in loop shaping to extend transparency bandwidth may not be useful in AUI interactions since the user is the limiting factor in determination of transparency. Finally, this paper presents the need for further considerations relating to kinematic nonlinearities, grip force at the man/machine interface, and priori modeling of the user.

III. Problem Definition

The transparency of the Phantom 1.0 A shall be measured for active (AUI) and passive (PUI) interactions with the manipulator. In so doing, the transparency will evaluate how well the Phantom 1.0 A can display force for a given frequency bandwidth for specific interaction types. Figure 2 shows the block diagram for an impedance based haptic simulation where X_H is the human displacement, Z_E is the environment impedance, F_D is the desired force, F_M is the measured force, and G_T is the transfer function of the manipulator. G_T also represents the transparency transfer function, which was defined earlier as the ratio of transmitted to simulated impedance. One should note that G_T cannot be explicitly defined because the system is not fully known as illustrated in Figure 3, which is simply a modification of a hybrid control system [11]. The unknown nature of the system relates to the kinematic, $Kin(\theta)$, and dy-

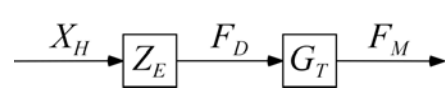

Figure 2: Block diagram of an impedance based haptic interaction

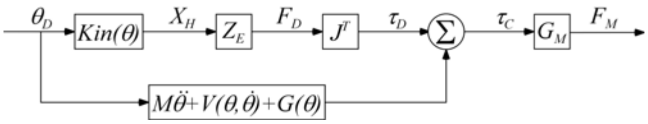

Figure 3: Kinematics and dynamics of impedance based haptic interaction

namic properties of the manipulator, the mass matrix, M, the Coriolis and centrifugal terms vector, V, and the gravity matrix, G; θ_D is simply the desired theta vector determined by the inverse kinematics of the manipulator itself from the human position, X_H. The reason that the kinematics of the manipulator are also a part of the transparency transfer function is related to the definition of transparency itself; the ratio of transmitted impedance to simulated impedance is given in Equation 1.

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

Ideally, G_T should be an identity matrix, but data from [7] and [10] show that this is not the case. Figure 3 shows that the measured force, F_M, is defined by the correct torque, τ_C, which is the sum of the desired torque, τ_D, and the torque due to manipulator dynamics, but it is possible to simplify Figure 3 and arrive at a more manageable measure of transparency. By assuming linearity of the Lagrangian near a particular operating point, small velocities, and gravity compensation of the manipulator, Figure 3 reduces to Figure 4. Figure 4 shows how the force determined from the environment impedance is actually output at the manipulator endpoint. As shown, J^T is computed in software, while $[J^T]^{-1}$ is a physical operation by the manipulator and is essentially G_M from Figure 3, which is the transfer function for the physical manipulator itself. When J^T is a non-linear matrix, the inverse is not always realizable; physically, force output errors could be introduced by assumption of linear kinematics.

The use of J^T alone in the computation portion of the system indicates that dynamics are not likely to be fully considered. In the general context of robotic control, position and force controlled robots both rely on the Lagrangian formulation of the manipulator dynamics as a means of efficient control of position, force, or both. However, if the device is assumed to have low inertia, high stiffness, and minimal friction, Figure 4 is a reasonable mathematical approximation of the physics of an impedance based haptic interaction. If these assumptions do not hold, particularly assumptions of small velocities and gravity compensation, then errors are introduced into the force output that would generally be compensated by velocity feedback.

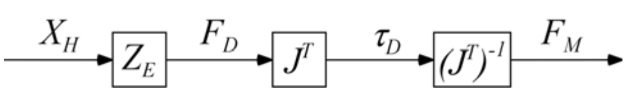

Figure 4: Simplified block diagram of impedance based haptic interaction

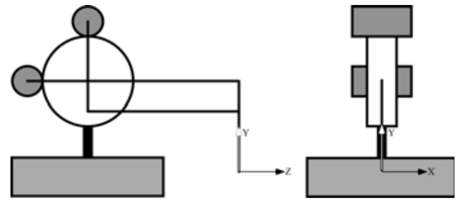

Figure 5: Phantom Premium with orientation axis in world frame

IV. Experimental Procedure

In order to evaluate the proposed transparency transfer functions above, a user was asked to interact with the Phantom Premium 1.0 A where the simulated environment was simply two springs oriented along a principle axis while constraining the other two axes with the stiffest environment possible; Figure 5 shows the orientation of the Phantom Premium in these directions. 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. For each interaction type (AUI and PUI) and constraint axis (X, Y, and Z), the user was asked to perform ten trials and results were then averaged to determine the transparency transfer function estimate. There were a total of six right-handed male subjects aged 20 to 27 who participated in the tests. In all the tests, 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.

A. Active (AUI) Test

In the active tests, subjects were instructed to move the stylus along the constrained axis, as in Figure 6, in a sinusoidal manner that increased in frequency similar to a chirp sine sweep. Subjects were visually cued by attempting to keep a solid sphere inside a larger wire frame sphere, which oscillated according to the desired chirp signal. The spring stiffness specified for these tests was 50 N/m. The length of the visual chirp was 10 seconds and used a hyperbolic ramp that ended at 30 Hz; force-sampling rate was 100 Hz with a haptic thread update rate of 1000 Hz. In addition, users were allowed to practice with the device before the tests to familiarize themselves with the device.

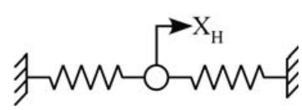

Figure 6: Spring environment oriented on X-axis for active (AUI) tests

B. Passive (PUI) Test

In the passive tests, the same compliant environment was used but here the chirp was applied directly as the desired force with an amplitude of 2N, as in Figure 7. During the test, the subject gripped the stylus and remained passive as forces were displayed. In addition, the user did not need any visual cues, and 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.

It is important to note that since the simulation controls the interaction, the overall transparency definition changes as well. Figure 8 shows the new block diagram. Note that displacement is now the output of the system, and a new parameter is included, Y_{HM}, which represents the admittance of the manipulator and the human linked together. This quantity is unknown, however, X_H, is a measurable property so transparency is defined as in Equation 2.

$$G_T = \frac{F_M}{F_C - X_H Z_E} \tag{2}$$

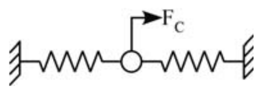

Figure 7: Spring environment oriented on X-axis for passive (PUI) tests

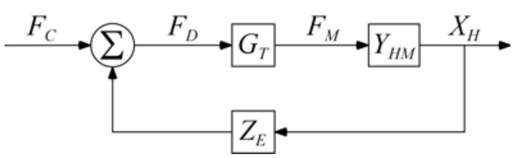

Figure 8: Block diagram of haptic interaction actively displaying force while user is a passive element

V. Results

Using the tests described above, the active (AUI) test revealed results that corroborated previous work [7]. The passive (PUI) test results, however, showed that transparency is different from its active counter-part.

A. Active (AUI) Test

In the active tests, the subject was asked to track a wire frame ball with the Phantom in an attempt to excite the manipulator within a desired frequency bandwidth. These tests showed that the estimated transparency transfer function bandwidth ranged from 2-5 Hz and was about 2 Hz when averaged over all subjects. Figure 9 shows a typical result with the expected model transparency calculated from the kinematic data. The transparency transfer function estimates showed differences between the constraint axes where X and Y generally had a lower bandwidth than the Z-axis. The data from 6 Hz and beyond looks like transducer induced noise; however, one must question the ability of a human being to supply displacements at frequencies of 6 Hz and beyond. Therefore, the displacement as function of frequency was also examined. Figure 10 shows that the displacement amplitude for the same typical test drops to below -50 dB between 2-4 Hz, which corresponds to the transparency bandwidth of the active tests.

B. Passive (PUI) Test

In the passive tests, the subject was asked to simply maintain a rigid grip on the stylus while allowing their forearm to be moved by the manipulator. The sine sweep in these

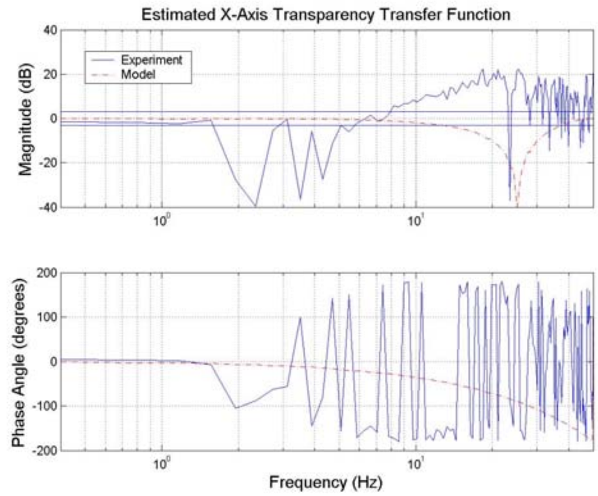

Figure 9: Estimated transparency of X-axis interaction in active test

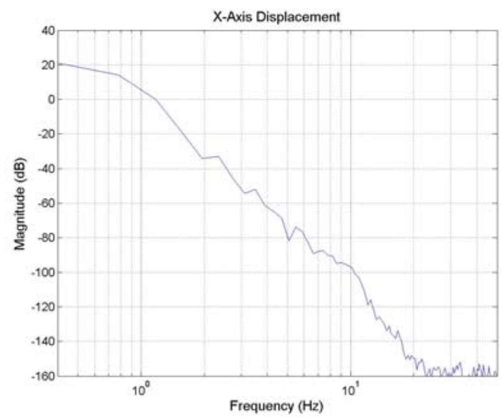

Figure 10: Typical X-axis displacement in an active test

tests ranged from 0 to 50 Hz. In these tests, the transparency transfer function did not have an appreciable cut-off frequency. This was not limited to a particular axis either; all constraint axes showed similar results. Figure 11 shows a typical result with the expected model transparency calculated from kinematic data. Again when analyzing the transparency transfer function frequency response plots, it is important to note that the phase information cannot be used to analyze stability since the transparency transfer function is a tool for measuring system performance, not a representation of the actual system dynamics. Transparency bandwidth seems to be at the discretion of the observer since, although gain crossover occurs, the transparency estimate remains close to the crossover gain until the higher frequencies where it is absolutely defined. As a means of comparison, the typical displacement plot is presented in Figure 12. The most noteworthy information is that the displacements are all above -50dB which agrees with the active test data showing that valid results were obtained when the displacements were greater than -50dB. As in the AUI case, a comparison to a model was made for the PUI case. The results presented in Figure 11 show that the transparency bandwidth of 25 Hz for the simulated dynamics is larger than that of the AUI case and matches the morphology and bandwidth of the measured transparency reasonably well.

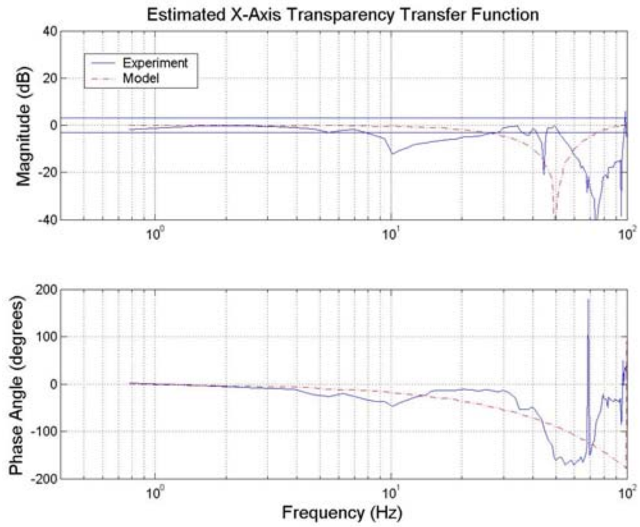

Figure 11: Typical estimated transparency of X-axis interaction in a passive test for measured and simulated manipulator dynamic forces

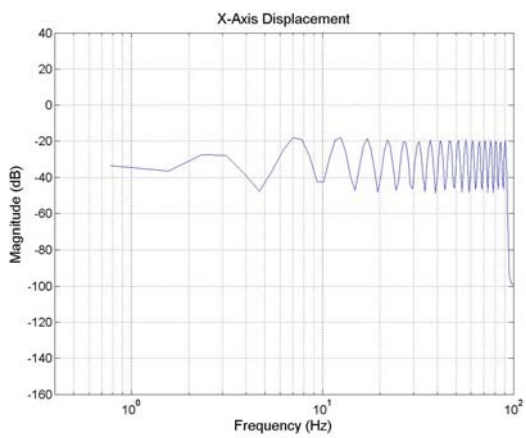

Figure 12: Typical X-axis displacement in a passive test

VI. Discussion

This study examining the transparency of the Phantom 1.0A haptic interface yielded some noteworthy information relating to assumptions about human interaction with haptic interfaces based upon transparency data.

A. Transparency Bandwidth

The data from the active (AUI) tests seem to indicate that transparency bandwidth is very small and is dependent upon the user. On the other hand, the data from the passive (PUI) tests seem to indicate that transparency bandwidth is not user dependent or small. The discrepancy could lie in the manner in which the tests were conducted, the particular environment chosen, or in assumptions about the man/ machine interface. In the case of the two test types, the primary difference is who or what commands displacement of the impedance-based manipulator since the environment is the same for both tests. In the AUI interaction, the human commands position and maintains force since it is a spring environment; in the PUI interaction, the simulation commands force. In both cases, any dissipative effects due to the human or the manipulator should be apparent, but this is not obvious from the data. The particular environment chosen could possibly explain differences, but again, it should be obvious in both the active and passive tests. However, no study has been conducted to evaluate the effect of various environments on transparency and stability. Future work will likely center on creating a study to verify multidimensional models created with respect to stiffness, dissipation, and inertial effects. The most likely reason for the aforementioned discrepancy lies in some basic assumptions about the man/machine interface.

B. Force Equilibrium

Hogan makes it clear that the equilibrium control criterion is a force balance at a port [14]. Hogan defines a manipulator interacting with an unconstrained inertial object; in our case, the unconstrained inertial object is the human. The argument of the human as an unconstrained inertial object is as follows. Obviously, the human has inertia, but the question of it being unconstrained requires assumptions regarding the status of the human as an admittance or an impedance operator. According to Hogan, the environment with which the manipulator interacts is an admittance when it commands position and an impedance when the environment commands force. It is obvious that when two systems interact at a port, one of the systems cannot specify both effort and flow; one must react to the other and vice versa. If the manipulator commands force as an impedance, the human must be an admittance since the two systems interact at a single port, in the case of the Phantom 1.0 A, the stylus. Therefore, the human must be an admittance to the manipulator, which commands force. Now, it should be stated that the human could switch modes as an admittance or an impedance since the human can contract muscles isotonically (command force) or isokinetically (command position) [15]. However, from the assumptions of impedance based haptic manipulators, it is obvious that the user commands position. Since this assumption must be true, the dynamics of the manipulator govern the display of the environment exclusively when the system is passively commanding force and the user is actively commanding position (AUI).

C. Insufficient Excitation

Given the validity of the above assumption, there are three possible reasons for the low transparency bandwidth in the active (AUI) tests: the manipulator dynamics are peculiarly influenced by a human controlling the interaction; delay in the control loop; or insufficient excitation by the human. It is possible that human control exerts some peculiar effect on manipulator dynamics due to coupling in other axis directions, but note, this is due to the manipulator dynamics alone reacting to human input. Indeed, another study will examine manual excitation of the manipulator by an external analog means that will constrain motion such that other axes will not play a significant role; furthermore, frequency excitation bandwidth will be guaranteed. Presumably, this will show that the non-linear attributes of the manipulator must be considered in the control algorithm. It is also possible that a delay exists in the haptic update loop between the position acquisition and motor command, but if this were the case, a zero-order hold instability would be obvious to the user and necessitate the use of a dissipative environment to guarantee stability. However, the human's inability to excite higher frequencies is most likely since an average human cannot initiate voluntary motion at frequencies higher than 5 Hz [1].

D. Passive Transparency

In the passive (PUI) tests, the user was subjected to a commanded force that was uniformly applied to the manipulator and the user with a feedback impedance; this is an event-based haptic interaction [16]. The transparency transfer function estimates varied slightly from user to user indicating that there is a problem endemic to the manipulator system in terms of maintaining transparency bandwidth regardless of the user. The slight differences between users would seemingly validate the use of a universal compensator to ensure that every user feels the same transmitted impedance. The transparency transfer function can be defined explicitly as in Equation 3.

$$G_T = \frac{F_M}{F_D} = \frac{F_M}{F_C - F_M Y_{HM} Z_E} \tag{3}$$

A range of users would feel the same commanded force, assuming a transparent manipulator, only when the environment impedance is zero. However, it is obvious from the transfer function that the transparency of the transmitted environment is fundamentally linked to the admittance of the user. Very low admittance on the part of the user would result in a transparency gain of unity, but this limiting case is unlikely, as it would be a large impedance that a human is not likely to emulate. This is the reasoning behind the question as to an individual user compensating mentally for transparency differences. However, knowing the user dynamics a priori may prove useful for extending transparency bandwidth as demonstrated by [13], [17], and [18]. As to the overall transparency of the manipulator, a test should be conducted without an environment to evaluate the performance of the electromechanical system defined as the transpose of Jacobian inverse.

VII. CONCLUSIONS

This paper investigates two measurement techniques for determining the transparency bandwidth of haptic interfaces. Specifically, active user induced (AUI) and passive user induced (PUI) interactions are studied. Prior work has predominantly used AUI techniques for determining system bandwidth, proposing linear compensators to improve the experimentally determined bandwidth of the human-haptic system. This paper questions the validity of AUI measurements of transparency when bandwidths beyond that which can be voluntarily excited by the human user are of interest. Specifically, these loop shaping techniques have been used to extend transparency bandwidth of haptic and teleoperation system beyond the range that is excitable by the human user, which indicates that the compensation is not for the system's inherent dynamic limitations but for the limitations of the user's voluntary motion excitation. The paper also discusses that a force balance must exist at the man-machine interface when the user is actively interacting with the haptic system. Because of this force balance, variability in human dynamics between users has no effect on the transmitted impedance during AUI measurements. The authors propose the use of PUI measurement techniques to ensure excitation of the full frequency range of the haptic system, and to enable compensation for hardware dynamics rather than human motion frequency limitations. With this measurement technique, human operator dynamics do indeed affect the transmitted impedance, however early experimental results indicate that variations between users are small.

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