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Experimental Comparison of Internet Haptic Collaboration with Time-Delay Compensation Techniques

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***Abstract*— In this paper we analyzed the performance of a peer-to-peer haptic collaboration system with two users jointly manipulating an object with mass and damping properties. We used objective measures to compare tuned PD, wave variables and time domain passivity controllers subject to real time delays from the Internet through similar experimental parameters. We set up a packet reflector network at our collaborators' servers in order to able to perform the experiment with subjects located in the same laboratory. Subjects were blinded to which controller was used and received them in a randomized sequence. UDP data packets were used for haptic data communication and the packet transmission rate was maintained at 1000 Hz. Our experimental results show that the tuned PD controller gave the best performance in terms of position error and wave variables in terms of force.**

I. Introduction

Networked haptic virtual environments (NHVEs), in which multiple users collaborate on a shared virtual space and at the same time experience force feedback, has the potential to be used in a wide variety of applications including surgical training [1], maintenance procedure training [2], and networked games. For example, maintenance procedure tasks for aircraft assembly could be done using a NHVE with experts operating from their usual locations, thus avoiding expensive travel and achieving effective time management.

The implementation of NHVEs has to overcome several challenging problems: Firstly, the overall system should be guaranteed to remain stable during the entire duration of the collaboration. Secondly, position coherency between the copies of the virtual object should be maintained all through the simulation. Otherwise, the copies of the virtual objects would start to drift from one another and the collaboration would become meaningless after a certain amount of time. Lastly, the haptic update rate would have to be maintained at 1000 Hz in order to feel stiffer objects [3] and this can require a significant portion of the available bandwidth of the network.

In our previous work we proposed *virtual coupling schemes* to enforce position coherency in two peer-to-peer and one client-server architectures and tested them with constant time delays [4], and on a global scale Internet connection [5] for three different packet transmission rates. Of the three virtual coupling schemes, we had shown in [4] that one of the peer-to-peer schemes is sensitive to communication delays. The virtual coupling parameters in our previous work were chosen so that the system resulted in a stable operation.

"Wave variables" [6] based on scattering transformation and passivity theory [7] guarantee stability under arbitrary communication delays. Recently in [8], [9] a time-domain passivity based method was proposed for stable bilateral control of teleoperators under time-varying communication delay. In this work, both methods were used to stabilize a peer-to-peer NHVE system.

A. Goals of this study

Our objective for this paper is to experimentally compare the performance of the peer-to-peer virtual coupling scheme implemented using a tuned PD controller and two different time delay compensation techniques, in terms of how well they minimize the error between the position of the virtual copy of a rigid body that multiple users share in a haptic virtual environment in time varying delay network conditions at a fixed transmission rate of 1000 Hz.

II. Background

There are several works in the area of NHVEs, each using a particular type of connection among the participants and force rendering techniques. We classify these works based on the connection architecture as either centralized (client-server) [10], [11] or distributed (peer-to-peer) [12], [13], [14], [15]. Based on the type of force rendering, they can be further classified into continuous [10], [11], [13], [4], [14], [16], [15] where users simultaneously manipulate a virtual object, and impulsive [12], where each user takes turns in manipulating the virtual object. In [4] and [16], both centralized and distributed architectures were used to study the NHVE. In [17], the wave variable based delay compensation technique was used to stabilize a cooperative haptic collaboration system.

Time delay compensation techniques have been well studied in bilateral teleoperation. Several techniques for time delay compensation for both constant and time-varying delay have been proposed. For more details on the methods the interested readers can refer to [18]. In [19], a detailed experimental comparison of Internet-based bilateral teleoperation using seven control architectures was performed.

III. Methods

The peer-to-peer virtual coupling scheme is shown in Fig. 1. The virtual environment consists of a simplified

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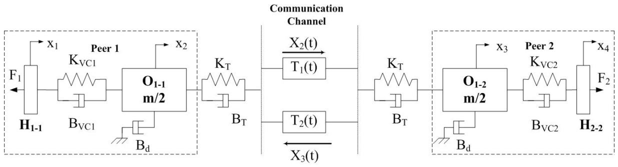


Fig. 1. Peer-to-peer scheme with PD control

collaboration model which supports two users with one degree of freedom. The virtual copy of the haptic device position is represented by haptic handles H_{1-1} and H_{1-2} while O_{1-1} and O_{1-2} represent the virtual copies of the rigid body with which both users interact. K_{VC1}, B_{VC1}, K_{VC2} and B_{VC2} are the virtual couplings that transmit forces to Users 1 and 2 respectively. An impedance-type haptic display is used to represent the interaction between the human operator and the haptic device. x_1 and x_4 represent the position of the haptic device while x_2 and x_3 represent the position of the virtual copies of the rigid bodies. Viscous damping B_d is added between the cube and the surface to keep the mass from drifting off when users are not in contact. The time varying delays between the peers are represented by $T_1(t)$ and $T_2(t)$ for forward and return paths.

A. PD control

The two virtual copies of the rigid body are connected by a virtual coupling (Fig. 1). This enables the virtual copies to track one another and also transmit forces between them. The masses of the virtual objects were equally divided between the virtual copies to ensure consistency in the total mass felt by each user. A position-position architecture was used to implement the virtual coupling network, which is similar to approaches in bilateral teleoperation [7]. Equations 1 to 4 demonstrate the reaction force applied to each user and the control force acting on the virtual objects.

$$F_1 = K_{VC1}(x_2(t) - x_1(t)) + B_{VC1}(\dot{x_2}(t) - \dot{x_1}(t)) \quad (1)$$

$$\frac{m}{2}\ddot{x_2}(t) = K_T(x_3(t - T_2(t)) - x_2(t)) + B_T(\dot{x_3}(t - T_2(t)) - \dot{x_2}(t)) - F_1 - B_d\dot{x_2}(t) \quad (2)$$

$$F_2 = K_{VC2}(x_3(t) - x_4(t)) + B_{VC2}(\dot{x_3}(t) - \dot{x_4}(t)) \quad (3)$$

$$\frac{m}{2}\ddot{x_3}(t) = K_T(x_2(t - T_1(t)) - x_3(t)) + B_T(\dot{x_2}(t - T_1(t)) - \dot{x_3}(t)) - F_2 - B_d\dot{x_3}(t) \quad (4)$$

B. Wave Variable Control (WV)

In wave variable control, the communication network was made stable for arbitrary delay by transmitting the wave variables instead of power variables across the network [6]. The wave transform encodes the velocity and force into wave variables at both ends before transmitting across the network. The wave variables are defined as:

$$u = \frac{b\dot{x} + F}{\sqrt{2b}} \qquad v = \frac{b\dot{x} - F}{\sqrt{2b}} \quad (5)$$

u and v are forward and returning waves from master to slave and vice versa. The wave impedance b is a positive constant that determines the properties of the communication line.

Fig. 2 shows the wave variable control implementation in the peer-to-peer NHVE system. The *Wave Transformation* blocks represent a symmetric wave variable implementation where the desired velocities of the virtual objects are extracted at locations 1 and 2. For this implementation u is computed at the User 1 end and v at User 2 end respectively. The corresponding wave variables are then transmitted across the network. In order to reduce wave reflection, the value of wave impedance b is chosen to be the same value of B_T.

C. Time domain passivity control (TDP)

In this compensation method for time varying communication delay for bilateral teleoperation, [9], the input energy at master and slave ports is calculated and transmitted across the network. The *Passivity Observer* (PO) then monitors the output energy at the master and slave ports and any excess energy is then dissipated using two series of *Passivity Controllers* (PC) attached to either end of the master and slave ports.

Figure 3 shows the implementation of the time domain PO/PC method for time delay compensation in a peer-to-peer NHVE. It can be shown that the sufficient conditions for maintaining stability in the above system are:

$$E_{in1}(k - D^{12}) \geq E_{out2}(k), \quad \forall k \geq 0 \quad (6)$$

$$E_{in2}(k - D^{21}) \geq E_{out1}(k), \quad \forall k \geq 0 \quad (7)$$

where k denotes the kth step of the sampling time t_k and D^{12} and D^{21} represent the communication delay from User 1 to User 2 and User 2 to User 1 respectively. The input energy at User 1 is monitored by the PO E_{in1} and transmitted across the network to User 2. The E_{out2} at User 2's end monitors the output energy and activates the damping element α_2 to dissipate excess energy. Similarly, the E_{out1} at User 1's end dissipates excess energy using the damping element α_1.

IV. Experiment Setup

The experimental collaborative haptic system is shown in Fig. 4. It consists of two workstations WS1 and WS2 used in the experiment by Users 1 and 2 respectively. WS1 is an AMD Opteron 1.5 GHz with 1 GB RAM and WS2 is an Intel Pentium 4 2.66 GHz with 1 GB RAM with both running Fedora Core 4 Linux. The two workstations are situated in the same laboratory but in different cubicles. A PHANToM Omni device was used for the experiments by each user; a 6 DOF sensing and 3 DOF force-rendering device. The peer-to-peer NHVE is implemented using a collaboration software framework (written in C++) and the network packet reflector setup that enables experiments using the Internet. The software framework performs collision detection, haptic UDP data communication and dynamic update of the virtual objects. For more detailed information

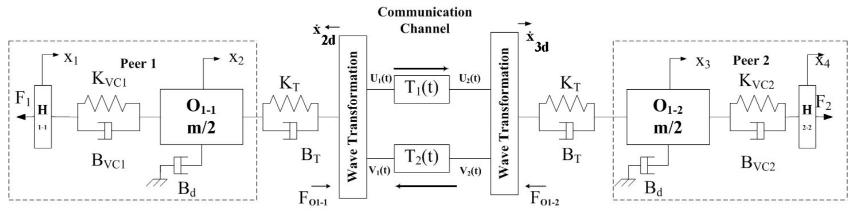


Fig. 2. Peer-to-peer scheme with wave variable delay compensation

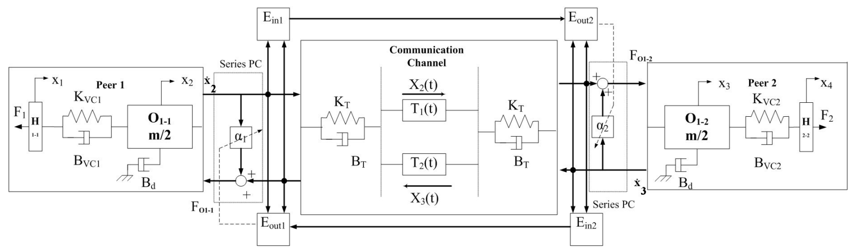


Fig. 3. Peer-to-peer scheme with time domain PO/PC delay compensation

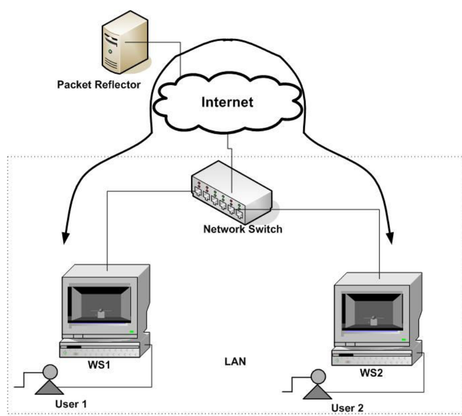


Fig. 4. Experiment setup

on the software framework, the interested readers can refer to [20].

Figure 5 shows the snapshot of the haptic virtual environment as seen by User 1. It consists of a cube that is restricted to one degree of freedom movement on a floor in a three dimensional room. The task of the users is to jointly move the cube along the line and to make the target align at the center of the cube at all times. The virtual environments also had additional attributes in order to aid the users during the experiments. The color of the cube — which is initially white— is changed to blue when the users make contact, and remains blue as long as the reaction force applied to the user exceeds 0.33N (to ensure that the users are in constant contact with the cube and contributing to the collaborations). The color of the cube changes to red when the user reaction force is greater than 3.3N (the maximum recommended continuous force for the Omni haptic device). The color of the target sphere changes from green to purple during tracking and the solid white line gives the user a hint about when the target is going to change direction.

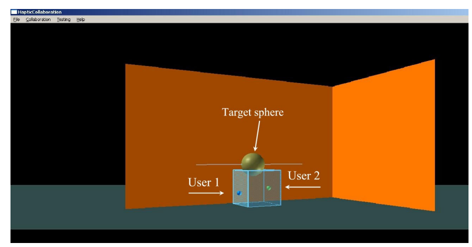


Fig. 5. Simulator snapshot

A. Packet Reflector Network

In order to test the NHVE system using the Internet, we have placed UDP packet reflector programs at the servers of our collaborators. The UDP packet reflector program receives the haptic data packets and routes them to predefined IP addresses. In this work, the packet reflector program routed packets between WS1 and WS2. The major advantages of these features are: Human subjects can be located in the same laboratory, which simplified recruiting, consistent enforcement of experiment protocol and procedures, and avoiding the usual issues of assorted time zones. Different networks with varying delays, number of hops and bandwidths can be tested seamlessly by switching between the packet reflectors during the experiment. The network topology of our packet reflector set up is shown in Fig. 6. It consists of two packet reflector locations, one at the North Carolina State University (NCSU), Raleigh, USA, and the other at the Scuola Sup. Sant'Anna (SSUP), Pontedera, Italy. The packets are transmitted to these points from the experimenters' location at the University of Washington (UW), Seattle, USA. The UW and the NCSU are partners in NLR (the National Lambda Rail), a gigabit research network. The connection between UW and SSSUP is through NLR, GEANT2 and GARR network (both European gigabit research networks); The two packet reflector locations along with the local network connection constitutes three time varying delay conditions whose values

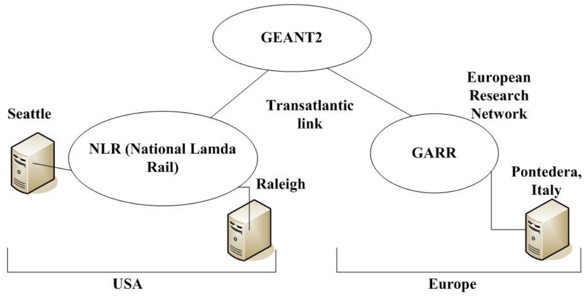


Fig. 6. Experiment network topology

obtained during the experiments using UDP packets appear in Table I.

TABLE I

DELAY CONDITION WITH PACKET REFLECTOR LOCATION

Delay Condition	WS 1		**Ping Time (1000 Hz)**
	Mean (ms)	Std (ms)	Mean (ms)
1 - Local	0.006	0.58	0.10
2 - NCSU	71.43	11.24	76.53
3 - Italy	182.72	1.84	189.65

V. EXPERIMENT PROCEDURE

Ten subjects, eight males and two females, with ages ranging from nineteen to fifty years old were selected for the experiment. Two subjects were left-handed and the rest were right-handed. The experimenter acted as User 1 and each subject as User 2.

Each subject was then given five practice trials to get comfortable with the virtual environment and the interaction with the cube. Their performance was monitored at the same time, and if they successfully completed five trials, then the practice trials were stopped and they proceeded to the actual experiment. They were asked to touch and apply forces on the right side of the cube as the experimenter interacted on the left side. The subjects were encouraged to maintain contact with the cube at all times. The target motion was enabled by the experimenter by pressing the button on the stylus of the Omni haptic device. Each subject waited for the change of color in the target to start moving. They were also instructed to apply less force when the color of the cube changed to red until it reverted back to blue. In order to reduce the learning effect, the order of the control methods and delay conditions were randomized for the experiments and loaded as a configuration file during the beginning of each experiment. Each subject was also asked complete a questionnaire at the end of the experiment for subjective evaluation of their experience in using the system.

The parameters used in the experiment are shown in Table II. In our previous work [4] we had analyzed the stability of the peer-to-peer NHVE and tuned the PD control parameter values such that the largest allowable one-way delay was about 200 ms. The three control methods were tested for two different sets of parameters and three delay conditions except the control method PD-B, which was unstable for the Delay condition 3. As a result, each subject performed 17 trials in this experiment. The position and velocity of the two cubes, along with the position of the target and forces rendered to each user, the number of corrupt, out-of-sequence and lost packets, and the delay in ms computed from the time stamp information were recorded in a file for later analysis.

In the initial testing with the time domain passivity controller with just K_T and no damping, the users were not able to collaborate in the NHVE because of the oscillations that were distracting. The damping added just to stabilize the system by the PC was not enough to reduce oscillation in our NHVE system. We chose to use the PD controller instead of just a P controller as used in [9] at both user ends.

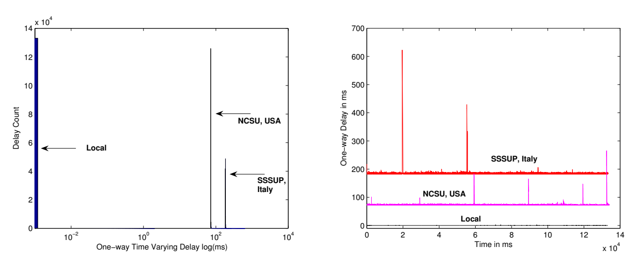
TABLE II

EXPERIMENT PARAMETERS

Parameters	**Values**	**Control type**	**Selection**
m	0.25Kg	All	experimental
B_d	$0.025\frac{Ns}{mm}$	All	experimental
K_{VC1}, K_{VC2}	$0.5\frac{N}{mm}$	All	device manual
B_{VC1}, B_{VC2}	$0.003\frac{Ns}{mm}$	All	device manual
K_T	$2.0\frac{N}{mm}$	All	experimental
B_T, b	$0.3\frac{Ns}{mm}$	PD-A, WV-A, TDP-A	experimental
	$0.15\frac{Ns}{mm}$	PD-B, WV-B, TDP-B	experimental

VI. RESULTS

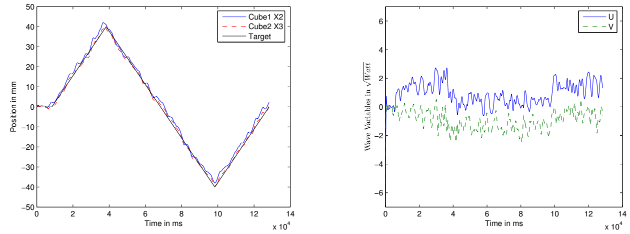
The histograms of the one-way delay between WS1 and WS2 for the three delay conditions are shown in Fig. 7(a). All the delay values had a peak value around their respective means and a long tail toward increasing delay. Fig. 7(b) shows the time-series plot of the measured delay during a trial. The large spikes in the measured delay are due to queuing delay at the routers in the Internet.



(a) **(b)**

Fig. 7. (a), Histogram of one-way time varying delay (b), Time series plot

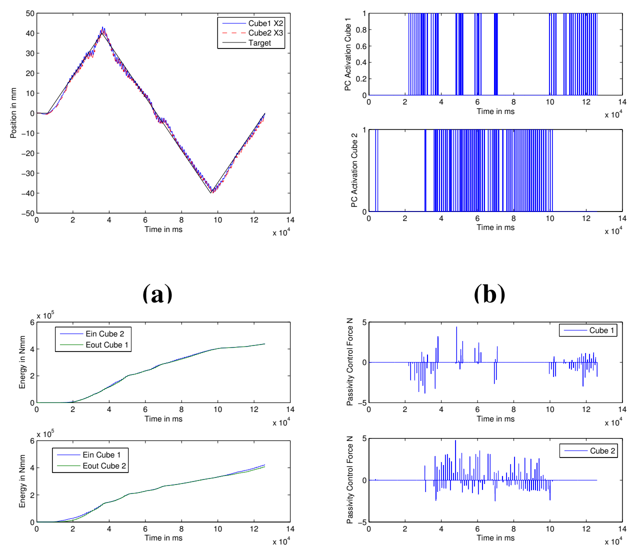
The position of the two cubes relative to the position of the target for delay condition 3 and for control type WV-A is shown in Fig. 8(a). The wave variables U and V from this trial are shown in Fig. 8(b).



(a) **(b)**

Fig. 8. (a), Tracking of the cubes for wave variables (b), wWave variables

Fig. 9(a), shows the position of the two cubes relative to the position of the target for delay condition 3 and control type TDP-B. The passivity controller action over the duration of the trial is shown in Fig. 9(b). The IO energy computed at both Cube 1 and 2 is shown in Fig. 9(c). The passivity controller force applied to Cube 1 and Cube 2 to keep the system stable is shown in Fig. 9(d).

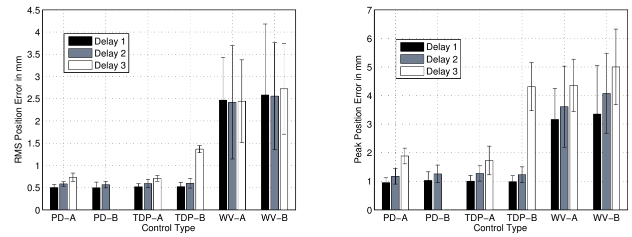


(c) **(d)**

Fig. 9. (a), Tracking of the cubes for TDP controller (b), PC action during the trial (c), The input and output energy at both user ends (d), Passivity control force applied to stabilize the system

Fig. 10(a) show the RMS position error between the positions of the cube x_1 and x_2 measured at User 1 for the control types A and B. The vertical bars represent the standard deviation around mean error values. The RMS position error increased for the control types PD and TDP with increasing delay time. For TDP-B, the value for delay condition 3 was substantially higher compared to TDP-A.

Repeated measures ANOVA of the results show that delay had significant effect on both PD and TDP control types. Moreover, both WV-A and WV-B were significantly different from the other control types. Furthermore, TDP-A was found to be significantly different from TDP-B, and between PD-A and PD-B no significant difference was found. Paired-sample t-test for delay condition 3 between WV-B and TDP-B confirmed that they are significantly different.

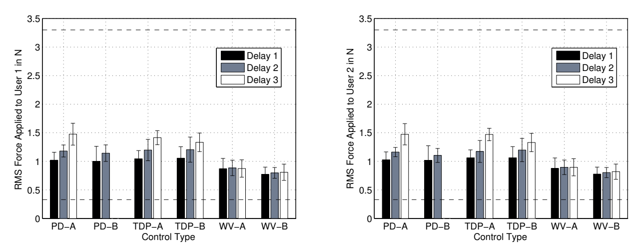


(a) **(b)**

Fig. 10. Position error between Cube 1 and Cube 2 measured at User 1 with parameters A and B, (a) RMS position error (b) Peak position error

Fig. 10(b) shows the peak position error between the cubes measured at User 1. For all the control types it increased with increasing delay time. For TDP-B, the value for delay condition 3 was substantially higher compared to TDP-A.

Repeated measures ANOVA show that delay had significant effect on all the three control types. Both WV-A and WV-B was found to be significantly different from PD-A, PD-B and TDP-A control types. We also performed a paired-sample t-test for the delay condition 3 between WV-B and TDP-B and they were found to be not significantly different with a p value of 0.226.



(a) **(b)**

Fig. 11. RMS Force rendered to the users with parameters A and B, (a) User 1 (b) User 2

Figs. 11 (a) and 11 (b) show the RMS Force applied to User 1 and 2 for the three control methods. The force values for User 1 and 2 increased on the whole with increasing delay time for control types PD and TDP. The control types WV-A and WV-B showed the least variation for increasing delay times.

Repeated measures ANOVA show that both WV-A and WV-B was found to be significantly different from PD and TDP control types. Between WV-A and WV-B no significant difference was found with a p value of 0.564 and 0.740 for Users 1 and 2 respectively.

VII. Discussion

In the experimental results, both WV-A and WV-B control method gave the highest RMS and peak position error between the two cubes. The forces rendered to both users were the lowest for the above methods. Because we used symmetric wave transformation and set the wave impedance equal to the damper value of the PD controller, the resultant wave impedance gave a high penalty for force at the expense of the velocity of the cube. The subjective feedback from users also confirms this as the users reported that during some of the trials, the cube was much more responsive than others.

Among the PD and TDP control methods, both PD-A and PD-B gave the lowest RMS and peak position error. The forces rendered to the users were much higher compared to WV control method. The performance of the TDP and PD controllers was not significantly different except for the case TDP-B with the global Internet delay condition. PD-B control was unstable but TDP-B control was stable with passivity controller acting to stabilize the system. The TDP-B controller gave large position errors, but less than that of wave variables. Also for the global Internet delay condition with TDP-B the damping provided by the passivity controller to stabilize the system was not sufficient to prevent oscillations during the collaboration. The subjective feedback from the experiments also confirm that during the trial, the oscillations were large enough to be a distractor for the collaborators.

We plan to mitigate the high position errors from the wave variable control by using wave variable with prediction [21] and control techniques based on [22]. In this work, only two users were considered. We plan to extend this work for more than two users in a NHVE. Moreover, in this work the haptic data packet transmission rate was fixed at 1000 Hz. In many networks, due to bandwidth limitations, sustaining a 1000 Hz packet transmission rate is not possible at all times. We plan to study the performance of the PD, WV and TDP control types at lower packet transmission rates.

Considering all three systems, the tuned PD controller gave the best performance in terms of position error and wave variables in terms of force.

VIII. ACKNOWLEDGMENTS

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