DIRECT USER-TO-USER HAPTIC INTERACTIONS VIA REMOTE DYNAMIC PROXIES OVER WAVE-DOMAIN COMMUNICATIONS

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Abstract—This paper investigates the stability of distributed direct user-to-user networked haptic interaction with remote dynamic proxies and passive wave domain communications. Considering fixed communication delays and fixed and low data transmission rate over the network, the paper develops the multirate state space model of the haptic system and uses eigenvalue analysis to determine the maximum stiffness of virtual contact that can be rendered to users. The analysis predicts that: (i) passive wave communications increase the maximum stiffness of the remote dynamic proxy coordination; (ii) the maximum contact and coordination stiffness are unaffected by fixed network delays; and (iii) the interacting users perceive smooth contact forces even for large network delays. Experiments in which two users probe each other with similar haptic interfaces validate the analytical results.

Keywords—direct user-to-user touch; distributed networked haptic systems; passive wave-domain communications; remote dynamic proxies;

I. INTRODUCTION

Haptic sharing of networked virtual environments is beneficial in applications like tele-therapy [1], virtual reality-based surgical training [2], multi-user online computer games with haptic feedback [3]. In these applications, networked users need both to cooperatively manipulate a shared virtual object and to directly interact with each other. For instance, in online ice hockey with haptic feedback, players need to touch other remote players in addition to hitting the virtual puck.

Both centralized [4] and distributed [5, 6] control architectures were proposed for haptic manipulation of shared virtual objects (SVOs). For power domain communications, several experimental studies investigated the impact of network delay, jitter, and packet loss on the stability and fidelity of networked haptic cooperation [7, 8, 9, 10, 11, 12]. Theoretical stability investigations were performed for multirate haptic cooperation across networks with constant delays and limited packet update rate [13], as well as for unirate haptic cooperation across the Internet [14]. The results in [13] indicate that distributed control can render stiffer virtual contacts than centralized control and thus, is advantageous for haptic cooperation in rigid virtual environments. The Internet-based haptic cooperation in [14] provides stable force feedback in static virtual environments. Torque feedback or interaction in dynamic virtual environments are not supported because the stability of the haptic cooperation is based on a passive integrator suitable for point interaction with virtual walls. For wave domain communications, distributed haptic cooperation was investigated experimentally in [15, 16, 10, 17], while centralized haptic cooperation was considered in [18]. The experimental studies confirmed the robustness to transmission delays of unirate haptic cooperation with wave domain communications. The analysis in [18] showed that aliasing needs to be prevented to ensure passive multirate wave communications when the network transmission rate is lower than the rate of the local force feedback loops.

In addition to haptic cooperation, direct user-to-user haptic interaction across a computer network was tackled in [19]. In that work, remote dynamic proxies (RDPs) were proposed as a means to mitigate the force discontinuities that arise because of the infrequent data received across the network from the remote user. RDPs are physically-based avatars of the remote users in the virtual environment of the local user. They are simulated at the rate of local haptic control loop at whom they reside, and are coordinated to the user whom they represent at the slow rate of data transmission over the network. Multirate analytical results and experiments in [20] show that the RDPs allow for stiff direct contact and render smooth motion of the remote peers in the presence of infrequent position and velocity information received across the network. However, multirate direct user-to-user networked haptic interaction becomes unstable when the communication delays increase. This paper shows that multirate direct haptic touch across a computer network becomes robust to
fixed delay if wave variables are transmitted between the remote users.

The work presented in the paper derives the range of control gains that guarantee stable direct user-to-user haptic interaction with passive wave domain communications and across a network with fixed communication delay and fixed and limited data transmission rate. The analysis uses the multirate framework introduced in [21] and first applied to haptic cooperation in [13]. The contributions of this work are: (i) the integration of passive wave communications into the distributed control of direct user-to-user haptic interaction with RDPs [20, 19]; (ii) the experimental validation of the analytical results. Both the analysis and the experiments demonstrate that passive wave domain communications can be used: (i) to make direct haptic touch between networked users robust to fixed communication delays; and (ii) to significantly increase the maximum stiffness of virtual contact rendered to users.

In the remainder of the paper, Section II. overviews the distributed passive wave domain control of direct user-to-user networked haptic interaction. Section III. derives the multirate state-space dynamics of direct touch with RDPs and passive multirate wave communications. Section B. presents the stability analysis. Section IV. experimentally validated the theoretical results. Section V. summarizes the results and discusses possible directions for future work.

II. DISTRIBUTED DIRECT USER-TO-USER TOUCH WITH REMOTE DYNAMIC PROXIES VIA PASSIVE WAVE-BASED COMMUNICATIONS

Scattered [22] or wave based [23] communications render the transmission channel passive in the presence of constant time delays. Scattered communications have been introduced to guarantee the stability of the interaction of any passive user with any passive remote environment under constant network delay presupposing haptic devices as passive elements in the loop. To maintain the wave communications passive when the network transmission rate is lower than the rate of the force control loop, anti-aliasing low-pass filters need to be placed before the rate drop [18]. Figure 1 depicts distributed direct user-to-user haptic interaction between two peers with remote dynamic proxies via passive wave-domain communications. In Figure 1: $T_d$ is the network delay; $F_{ICi}$ is the contact force applied to the Peer $i$; $F_{RDPji}$ is the coordination force applied to the remote dynamic proxy residing at Peer $i$ site; $\hat{x}_{ij}$ is the desired velocity of the remote peer $j$-th decoded from the wave signal received at Peer $i$ site; $u_{inj}$ and $u_{ouij}$ are arriving waves at Peer $i$; $u_{outj}$ and $u_{outij}$ are outgoing waves at Peer $i$ with proper indexes respectively; $M$ is the decimator factor representing the number of discarded consecutive samples from the input signal; LPs are anti-aliasing low-pass filters with cutoff frequency $\Omega_s = \pi/M$ which guarantee the passivity of the multirate wave-domain communications [18]; and $y_{il}$ and $y_{ij}$ are the output of the anti-aliasing filters with appropriate indexing.

In the next section, the state-space dynamics of distributed haptic direct touch with RDPs via passive multirate wave-domain communications are derived to determine the maximum stable coordination gains. Note the multirate state-space matrices of the direct user-to-user architecture with RDPs via power-domain communications for the results shown in Section B. can be derived easily by straight simplification of equations driven in Section III. and are not presented here for brevity.

III. MULTIRATE STATE-SPACE DYNAMICS OF DISTRIBUTED HAPTIC DIRECT TOUCH WITH REMOTE DYNAMIC PROXIES VIA PASSIVE WAVE-BASED COMMUNICATIONS

The derivations in this section are based on the approach introduced in [21] and are detailed only as much as needed for the integration of the passive wave domain communications.

A. Discrete-time state-space representation

The network sampling interval $T_n$ is assumed to be a multiple integer of the sampling interval $T_c$ of the users’ local force control loops. Their values are selected to match the experimental testbed in Section IV., and are $T_c = 0.001 \mathrm{s}$ and $T_n = 0.008 \mathrm{s}$. The discrete-time open loop state-space model of direct user-to-user haptic interaction is obtained by multirate discretization of the continuous-time state-space matrices in Appendix A, in the following form:

$$
\begin{align*}
\mathbf{x}_{D_{64 \times 1}}[k+1] &= A_{D_{64 \times 64}} \cdot \mathbf{x}_{D_{64 \times 1}}[k] + B_{D_{64 \times 1}} \cdot \mathbf{u}_{D_{64 \times 1}}[k] \\
\mathbf{y}_{D_{64 \times 1}}[k] &= C_{D_{64 \times 64}} \cdot \mathbf{x}_{D_{64 \times 1}}[k] + D_{D_{64 \times 1}} \cdot \mathbf{u}_{D_{64 \times 1}}[k]
\end{align*}
$$

(1)

where the index $D$ defines the discrete vectors and matrices, and $k$ represents the $k$-th network update interval. For detailed derivations of the system matrices $A_D$, $B_D$, $C_D$ and $D_D$, refer to [21]. The computational and communication delays are incorporated in Equation (1) as described in [13]. The decoded desired discrete-time velocities are:

$$
\hat{x}_{ij}[k+1] = \frac{F_{RDPji}}{k} + \sqrt{\frac{2}{T_n}}u_{inij}[k]
$$

(2)

and the desired positions are obtained from them through discrete-time integration after unwrapping the algebraic loop typical in wave transformations:

$$
x_{ij}[k+1] = T_c \cdot \hat{x}_{ij}[k] + x_{ij}[k]
$$

(3)

The desired position and velocities are included in the discrete-time state-space dynamics of the distributed haptic system through augmenting the state vector:

$$
\mathbf{x}_{D_{64 \times 1}}[k] = \begin{bmatrix} x_{D_{64 \times 1}}[k] \\ \dot{x}_{D_{64 \times 1}}[k] \end{bmatrix}
$$

(4)

where $x_{2 \times 1}[k] = (x_{12}[k] \ x_{12}[k])^T$, and the input vector is:

$$
\mathbf{u}_{D_{64 \times 1}}[k] = \begin{bmatrix} u_{D_{64 \times 1}}[k] \ u_{D_{64 \times 1}}[k] \ x_{D_{64 \times 1}}[k] \ u_{inij}[k] \end{bmatrix}^T
$$

(5)
The augmented output matrix is then:
\[ \mathbf{y}_{\text{aug}}[k] = \begin{bmatrix} \mathbf{x}_{\text{aug}1}[k] \\ \mathbf{x}_{\text{aug}2}[k] \\ \mathbf{u}_{\text{aug}1}[k] \\ \mathbf{u}_{\text{aug}2}[k] \end{bmatrix} \]

The discrete time open-loop dynamics including the anti-aliasing filters becomes:
\[ \begin{align*}
\mathbf{x}_{\text{aug}1}[k + 1] &= \mathbf{A}_{\text{D}1} \mathbf{x}_{\text{aug}1}[k] + \mathbf{B}_{\text{D}1} \mathbf{u}_{\text{aug}1}[k] \\
\mathbf{y}_{\text{aug}1}[k] &= \mathbf{C}_{\text{D}1} \mathbf{x}_{\text{aug}1}[k] + \mathbf{D}_{\text{D}1} \mathbf{u}_{\text{aug}1}[k]
\end{align*} \]

where \( \mathbf{y}_{\text{aug}} = (\mathbf{y}_{11}[k] \quad \mathbf{y}_{12}[k] \quad \mathbf{y}_{21}[k] \quad \mathbf{y}_{22}[k])^T \), and \( \mathbf{A}_{\text{D}} \), \( \mathbf{B}_{\text{D}} \), \( \mathbf{C}_{\text{D}} \), and \( \mathbf{D}_{\text{D}} \) are block-diagonal matrices with their corresponding difference matrices from Equation (22) in Appendix B.

**B. Stability regions**

The stability of the multirate two-user networked haptic interaction with RDPs via passive wave-domain communications can be derived through eigenvalue analysis of the closed-loop state transition matrix \( \mathbf{A}^j_{\text{D}} \), calculated via:
\[ \mathbf{A}^j_{\text{D}} = \mathbf{A}_{\text{D, aug}} + \mathbf{B}_{\text{D, aug}} \cdot \mathbf{F}_D \cdot (I - \mathbf{D}_{\text{D, aug}} \cdot \mathbf{F}_D)^{-1} \cdot \mathbf{C}_{\text{D, aug}} \]

where \( \mathbf{F}_D \) represents the feedback matrix and \( \mathbf{A}_{\text{D, aug}} \), \( \mathbf{B}_{\text{D, aug}} \), \( \mathbf{C}_{\text{D, aug}} \), and \( \mathbf{D}_{\text{D, aug}} \) are the state transition matrices obtained after...
suitable augmentation with computational and communication delays. Direct touch with RDPs via passive wave-domain communication is stable iff all eigenvalues of $A_D^T$ are less than unity in magnitude.

In the analyses presented in next section, the calculations are performed using the following parameter values: $m_{HD} = m_{RDP} = 0.1 \text{ kg}; b_{HD} = b_{RDP} = 0.5 \text{ Ns/m}; B_{LC} = B_{RDP} = 3 \text{ Ns/m}; b = 5 \text{ Ns/m}; \Omega_c = 60 \text{ Hz}$. Also, computational delays equal to one step of control loop sampling time are considered at each Peer as well as constant communication delays of $T_d$ equal to various multiples $n_t$ of the network packet update interval, $T_d = n_t T_n$.

C. Stability of direct touch with remote dynamic proxies via passive wave-domain communications

The stability regions of distributed direct user-to-user haptic interaction with RDPs are depicted in: (i) Figure 2a with power-domain communications; and (ii) Figure 2b with passive wave-domain communications. Both plots represent the effect of communication delay, $T_d$, on the stability regions. In particular, Figure 2a depicts the stability regions for distributed control of direct user-to-user touch with RDPs via power-domain communications where the contact force only includes the fast updated information (i.e., the states of both haptic device and the remote dynamic proxy are being updated at the local control feedback rate). However, the maximum stable RDP gain, $K_{RDP}$, decreases as the communication delay increases. This is because a part of coordination force, $F_{RDP}$, is calculated based on the states received from the remote haptic device read from network packets with limited transition rate. The stability regions for distributed control of direct user-to-user touch with RDPs via passive wave-domain communications are presented in Figure 2b. These results predict that by incorporating the passive wave-domain communications: (i) the maximum allowable stiffness of the virtual contact as well as the RDP coordination are increased; (ii) the maximum contact and coordination stiffness stay unaffected by fixed network delays. Such theoretical observations are validated through experiments next.

IV. EXPERIMENTS

This section validates the analytical results presented in the previous section through experimental one degree of freedom (DOF) distributed haptic interaction. The experiments contrast distributed direct user-to-user architecture with RDPs when using both passive wave-domain and power-domain communications. To allow meaningful comparison among successive experiments, two users are replaced by forces applied to haptic devices as commands sent to the servo motors. Note that the elimination of human hand damping integrates the worst case scenario for testing the stability since in the experimental setup, two impedance-type haptic devices are used.

A. Experimental setup

Figure 3 depicts the experimental testbed comprising two Quanser 6 DOF haptic wands connected to two personal computers running Window XP on an Intel Core 2 Duo CPU at 2.67 GHz with 2 GB RAM. The two computers communicate over a local area network (LAN) via the UDP protocol. The position sensing and force feedback rates for both haptic devices are set to 1 kHz. The network data transmission rate is 125 Hz. In all experiments, proportional-derivative controllers constrain the 6-DOF haptic devices to move only along the horizontal x-direction (parallel to the back wall in Figure 3). The virtual environment consists of the avatars of haptic devices depicted by virtual spheres. In the experiments, the damping of all couplers is set to 3 Ns/m and the wave impedance is $b = 5 \text{ Ns/m}$.

B. Stability tests

At the beginning of each experiment, two haptic devices are initially set at rest and in contact with each other. Each peer pushes the other with a constant force equal to 0.1 N applied via programming. At each user side, the RDP simulation uses forward Euler integration with fixed step equal to $T_c$. Mass and damping of the $i$-th RDP are set to $m_{RDP} = 0.1 \text{ kg}$, $b_{RDP} = 0.5 \text{ Ns/m}$ respectively. During the direct peer-to-peer interaction, Peer 1 applies an additional force equal to 1 N force towards Peer 2 for 25 ms at intervals of 2.5 s. With round trip network delay of $T_d = 0.016 \text{ s}$, stable gains are used for direct user-to-user interaction with RDP: (i) in Figure 4a via power-domain communications with contact gain $K_{LC} = 1000 \text{ N/m}$ and coordination gain $K_{RDP} = 300 \text{ N/m}$; (ii) in Figure 5a via passive wave-based communication with contact gain $K_{LC} = 1000 \text{ N/m}$ and coordination gain $K_{RDP} = 3000 \text{ N/m}$. For both cases, the round trip network delay is pushed up to $T_d = 0.128 \text{ s}$ as depicted in Figures 4b and 5b. Direct user-to-user interaction with RDPs over power-domain communications becomes unstable with larger delays, as in Figure 4b. However, incorporating passive wave-domain communications allows for larger maximum coordination gains, $K_{RDP}$, independent of network delays. In particular, RDP scheme over passive wave-domain communications provides increased and robust coordination between the local haptic device and its corresponding remote dynamic proxy. The results in Figure 5 validate that RDPs via passive wave-domain communications:
(i) makes direct haptic touch between networked users robust to fixed communication delays; and (ii) significantly increases the maximum stiffness of the RDP coordination force. Larger coordination gain increases the coherency between the position of haptic devices and their remote dynamic proxies. This can be observed in Figure 5 where the positions of the haptic devices and their corresponding RDPs are almost overlapped.

V. CONCLUSIONS

This paper has studied the use of passive multi-rate wave communications for distributed direct peer-to-peer haptic interactions with remote dynamic proxies connected over a network with limited transmission rate and constant communication time delays. Stability analysis is performed within the multirate state space model of the haptic system. Comparing to interactions over power-domain communications, the analysis predicts that direct user-to-user interactions over passive wave-domain communications: (i) allow for significantly larger stable RDP coordination gains; and (ii) provide the robustness of direct haptic touch to fixed and constant communication delays. Experiments performed with two users via two identical haptic interfaces validate the multirate analytical results. Future work will investigate the performance analysis of distributed direct user-to-user haptic interactions over passive wave-domain communications.

VI. APPENDICES

A. OPEN-LOOP CONTINUOUS-TIME STATE-SPACE MATRICES OF DIRECT USER-TO-USER TOUCH WITH REMOTE DYNAMIC PROXIES OVER WAVE-DOMAIN COMMUNICATIONS

To obtain the continuous-time state space dynamics of the open-loop direct user-to-user haptic interaction with remote dynamic proxies over passive wave-based communications, the dynamics of the users, remote dynamic proxies, and wave variables are grouped into fast and slow inputs and outputs, denoted with the indices $c$ and $n$ respectively. Specifically, the system inputs comprise: (i) the contact forces updated at the fast haptic rate; and (ii) the coordination forces applied to the remote dynamic proxies including both fast and slowly updated components.

$$ u^T = (u_c^T u_n^T)^T $$

(12)

where:

$$ u_c^T = (F_{LC1} F_{RDP21c} F_{LC2} F_{RDP12c})^T $$

$$ u_n^T = (F_{RDP21n} F_{RDP12n})^T $$

(13)

in which

$$ F_{LCi} = K_{LCi}(x_i - x_{RDPji}) + B_{LCi}(\dot{x}_i - \dot{x}_{RDPji}), $$

(14)

and

$$ F_{RDPji_c} = K_{RDP}x_{RDPji} + B_{RDP}\dot{x}_{RDPji} $$

$$ F_{RDPji_n} = -K_{RDP}\dot{x}_{jd} - B_{RDP}x_{jd} $$

(15)
The state vector comprises the states of all haptic interfaces and all remote dynamic proxies:

\[
x^T = (x_1^T, x_2^T)
\]

where:

\[
x_i^T = (x_i, \dot{x}_i, x_{\text{RDP}}; i, j)\]

The output vector is defined to only include fast states as:

\[
y = y_c = x_c
\]

Hence, the continuous-time state-space model of the open-loop is:

\[
\begin{align*}
\dot{x}_{k+1} &= A_{k \times k} x_{k \times 1} + B_{k \times n} u_{k \times 1} \\
y_{k \times 1} &= C_{k \times k} x_{k \times 1}
\end{align*}
\]

### B Multirate State-Space Matrices of Anti-aliasing Low-Pass Filters

The state-space continuous-time dynamics of the anti-aliasing filter \(i\)-th is defined as:

\[
\begin{align*}
\dot{x}_{li} &= -\Omega_c x_{li} + u_{\text{out}} \\
y_{li} &= \Omega_c x_{li}
\end{align*}
\]

where \(\Omega_c\) is the cutoff frequency of the LP filter. The following relationship holds between variable samples and filters’ outputs:

\[
u_{\text{out}}(t) = y_{li}(t - T_d)(M \downarrow)
\]

and \(T_d\) is the network delay. Since \(T_n = 8 \cdot T_c\), the discretized multi-rate difference state equations of the anti-aliasing filters are:

\[
\begin{align*}
x_{D_{8 \times 8}}[k + 1] &= A_{D_{8 \times 8}} \cdot x_{D_{8 \times 8}}[k] + B_{D_{8 \times 8}} \cdot u_{\text{out}_{8 \times 1}}[k] \\
y_{D_{8 \times 8}}[k] &= C_{D_{8 \times 8}} \cdot x_{D_{8 \times 8}}[k] + D_{D_{8 \times 8}} \cdot u_{\text{out}_{8 \times 1}}[k]
\end{align*}
\]

where indexes \(c\) and \(n\) correspond to the fast and slow sampling intervals respectively.

### References


