Passive Bilateral Teleoperation With Constant Time Delay

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***Abstract*—We propose a novel control framework for bilateral teleoperation of a pair of multi-degree-of-freedom nonlinear robotic systems under constant communication delays. The proposed framework uses the simple proportional-derivative control, i.e., the master and slave robots are directly connected via spring and damper over the delayed communication channels. Using the controller passivity concept, the Lyapunov–Krasovskii technique, and Parseval's identity, we can passify the combination of the delayed communication and control blocks altogether robustly, as long as the delays are finite constants and an upper bound for the round-trip delay is known. Having explicit position feedback through the delayed P-action, the proposed framework enforces master–slave position coordination, which is often compromised in the conventional scattering-based teleoperation. The proposed control framework provides humans with extended physiological proprioception, so that s/he can affect and sense the remote slave environments mainly relying on her/his musculoskeletal systems. Simulation and experiments are performed to validate and highlight properties of the proposed control framework.**

***Index Terms*—Bilateral teleoperation, communication delays, extended physiological proprioception (EPP), Lyapunov–Krasovskii functionals, Parseval's identity, passivity, proportional-derivative (PD) control.**

I. Introduction

ENERGETICALLY, as illustrated in Fig. 1, a closed-loop teleoperator is a two-port system with the master and slave ports being coupled with the human operators and slave environments, respectively. Therefore, the foremost and primary goal of the control (and communication) design for the teleoperation should be to ensure interaction safety and coupled stability [1] when mechanically coupled with a broad class of slave environments and humans.

To ensure such interaction safety and stability, energetic passivity (i.e., mechanical power as the supply rate [2]) of the closed-loop teleoperator has been widely used as the control objective (e.g., [3]–[11]). This is due to the property of the passive systems [12]: a feedback interconnection of *any* passive systems (with compatible supply rates) is necessarily stable (and also passive). In the context of teleoperation, this property implies that if we ensure energetic passivity of the closed-loop teleoperator, its mechanical interaction with *any* passive environments and humans will be necessarily stable (i.e., bounded interaction velocity), regardless of how uncertain and complicated their dynamics are. In many practical applications where the slave environment is passive (e.g., pushing a wall or grasping a ball) and the humans' mechanical impedance is indistinguishable from that of passive systems [13], this passivity of the closed-loop teleoperator indeed results in stable interaction. Energetically passive teleoperators would also be safer to interact with, since the maximum extractable energy from it is bounded, and so is the possible damage on the slave environments and humans.

In this paper, we consider the cases where the forward (i.e., from master to slave) and backward (from slave to master) communication signals undergo their respective finite constant time delays. One example of such cases is when the master and slave environments are located so far from each other that it takes non-negligible time for the communication signals to travel between the two environments (e.g., space teleoperation [14]). The other example is when the delays are varying but still bounded, so that by buffering data up to certain (known) worst-case maximum delays with time stamping, apparent delays can still be made constant (e.g., Internet teleoperation with insignificant packet loss [15]).

In [16]–[18], an H-∞ and μ-synthesis, Nyquist-based criteria, and results from linear time-delay systems are respectively used to ensure the interaction stability of the teleoperation with constant time delays, where the slave environments and humans are assumed to be known linear time-invariant (LTI) systems. Thus, their applicability would be limited in many practical applications where the dynamics of the slave environments and/or humans are often time-varying, nonlinear, and even unknown. To ensure interaction stability (and safety) with such complicated and possibly unknown slave environments and/or humans, it is again desired to enforce passivity for the delayed teleoperation.

How to ensure energetic passivity of the time-delayed bilateral teleoperation was a long-standing problem. In [3], energetic passivity of the delayed teleoperation is achieved by passifying the communication block with (possibly unknown) finite constant time delays. This passification was made possible by applying scattering theory. In [4], this scattering-based result is further extended, and the notion of the wave variables was introduced. Since these two seminal works, scattering-based (or wave-based) teleoperation has been virtually the only way to enforce energetic passivity of the time-delayed bilateral teleoperation (e.g., [5], [6], [15], and [19]–[22]).

Manuscript received June 9, 2004; revised July 12, 2005. This paper was recommended for publication by Associate Editor C. Melchiorri and Editor I. Walker upon evaluation of the reviewers' comments. This work was supported in part by the Office of Naval Research under Grants N00014-02-1-0011 and N00014-05-1-0186, in part by the National Science Foundation under Grants IIS 02-33314, CCR 02-09202, and ECS-01-22412, and in part by the College of Engineering of the University of Illinois.

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Digital Object Identifier 10.1109/TRO.2005.862037

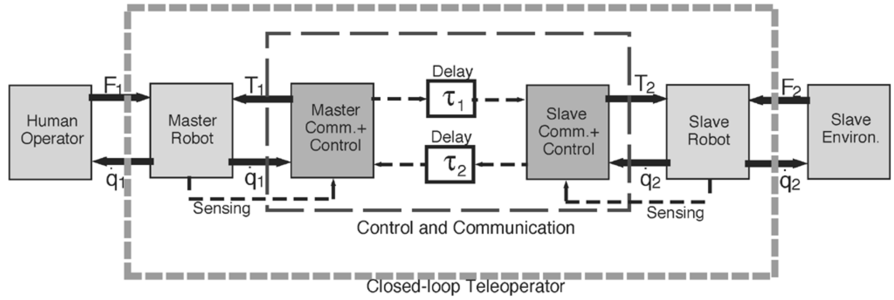

Fig. 1. Closed-loop teleoperator as a two-port system, where the dotted arrows represent information flow through the delayed communication channels, while solid arrows represent mechanical power pairs.

In this paper, we propose a novel control framework for bilateral teleoperation of a pair of multi-degree-of-freedom (DOF) nonlinear robotic systems with finite constant communication delays. The proposed framework is based on the simple proportional-derivative (PD) control, i.e., directly connecting the master and slave robots via spring and damper over the delayed communication channels. Then, using the controller passivity concept [11], [23], the Lyapunov–Krasovskii technique for the delayed systems [24], and Parseval's identity [25], we can enforce energetic passivity of the closed-loop teleoperator as long as the communication delays are finite constants and an upper bound of the round-trip delay (i.e., sum of the forward and backward delays) can be known, even if the delays are asymmetric (i.e., forward delay $\neq$ backward delay) and/or their exact estimates are not available. Moreover, by relying on the controller passivity concept, this passivity is ensured even in the presence of model parametric uncertainty (i.e., robust passivity [11], [23] is achieved).

A similar delayed PD control was used in [26], but passivity was not achieved there. In [27], we proposed a PD-based teleoperation control law, which is also able to enforce energetic passivity of the time-delayed bilateral teleoperation without being scattering-based. However, this control law, proposed in [27], assumes the communication delays to be exactly known and symmetric. In this paper, this often-unrealistic assumption is removed, as stated in the above paragraph.

The main advantage of the proposed framework is the explicit position feedback through the delayed P-control action (i.e., spring term with delayed set position). The lack of such explicit position feedback has been known as the major drawback of the conventional scattering-based teleoperation, in which, roughly speaking, the velocity information is extracted from the communicated scattering variables, and then integrated to recover the set position information. Therefore, if this integration becomes inaccurate (e.g., slave robot makes a hard contact with a rigid wall or communication is blacked out shortly), the master and slave positions may start drifting away from each other (see [28], for example). Having the explicit position feedback, our proposed framework would prevent such a position drifting. This explicit position feedback also enables us to guarantee (i.e., theoretically prove) asymptotic master–slave position coordination.

In contrast to the scattering teleoperation, where the delayed communication block is passified so that the closed-loop teleoperator becomes an interconnection of passive submodules (i.e., passified communication, passive control, and passive master/slave robots), the proposed framework passifies the combination of the communication and control blocks altogether. While the scattering-based teleoperation can be used without any knowledge of the (finite, constant) delays, our proposed framework requires knowing an upper bound of the round-trip delay. However, we think that this is a mild restriction, since, in many practical applications, round-trip delay is relatively easy to measure/estimate [29].

Although it achieves at least a level of ideal transparency [5], [17], the main goal of the proposed control framework is to provide humans with extended physiological proprioception (EPP) [30], i.e., the closed-loop teleoperator as a tool, by which the human operator can affect and sense the remote slave environments, mainly relying on her/his musculoskeletal systems. Note that the ideally transparent closed-loop teleoperator should not possess such an intervening tool dynamics [31], as it would alter the impedance perceived by the human from that of the slave environment. In this sense, the proposed framework is along the line of such research work as "common passive mechanical tool" [10], [11], "task-oriented virtual tool" [9], and "virtual tool for wave-based teleoperation" [19].

The rest of this paper is organized as follows. The control problem is formulated in Section II, and the control law is designed and its properties are detailed in Section III. Simulation and experimental results are presented in Section IV to validate/highlight properties of the proposed framework, and Section V contains a summary and concluding remarks.

II. Problem Formulation

A. Modeling of Teleoperators Under Constant Time Delay

Let us consider a teleoperator consisting of a pair of n-DOF nonlinear robotic systems

$$M_1(q_1)\ddot{q}_1(t) + C_1(q_1,\dot{q}_1)\dot{q}_1 = T_1(t) + F_1(t) \quad (1)$$
$$M_2(q_2)\ddot{q}_2(t) + C_2(q_2,\dot{q}_2)\dot{q}_2 = T_2(t) + F_2(t) \quad (2)$$

where $q_1, q_2 \in \Re^n$ are the configurations, $F_1, F_2 \in \Re^n$ are the human/environmental forcing, $T_1, T_2 \in \Re^n$ are the controls, $M_1(q_1), M_2(q_2) \in \Re^{n\times n}$ are the symmetric and positive-definite inertia matrices, and $C_1(q_1,\dot{q}_1), C_2(q_2,\dot{q}_2) \in \Re^{n\times n}$ are the Coriolis matrices of the master and slave systems, respectively. Due to its structure inherited from the Euler–Lagrangian dynamics, the jkth element of the Coriolis matrices $C_i(q_i, \dot{q}_i)$ in (1) and (2) are given by [32]

$$C_i^{jk}(q_i, \dot{q}_i) = \sum_{m=1}^{n} \frac{1}{2} \underbrace{\left[\frac{\partial M_i^{jk}}{\partial q_i^m} + \frac{\partial M_i^{jm}}{\partial q_i^k} - \frac{\partial M_i^{km}}{\partial q_i^j} \right]}_{=:{}^i\Gamma^j_{km}(q_i)} \dot{q}_i^m \quad (3)$$

for $i = 1, 2$ and $j,\ k = 1, 2, \ldots, n$, where ${}^i\Gamma^j_{km}(q_i)$ are the Christoffel symbols (of the first kind) with the symmetric property such that (s.t.) ${}^i\Gamma^j_{km}(q_i) = {}^i\Gamma^j_{mk}(q_i)$. Also, from (3), we have the well-known passivity property, i.e., $\dot{M}_i(q_i) - 2C_i(q_i, \dot{q}_i)$ are skew-symmetric.

We assume that, following the procedures in [10] and [11], suitable bilateral motion and/or power scalings have been already embedded in the dynamics (1) and (2) to match different kinematic sizes and/or mechanical strengths between the master and slave environments (e.g., MEMS teleoperation). For the dynamics (1) and (2), we also assume that the gravity terms are either included in the forcing terms $F_1(t)$, $F_2(t)$ or precompensated by the local controls.

In this paper, we assume the communication structure as shown in Fig. 1, where the forward and backward communications are delayed by finite constant time delays $\tau_1 \geq 0$ and $\tau_2 \geq 0$, respectively. Then, the controls $T_1(t)$, $T_2(t)$ in (1) and (2) can be defined as functions of the current local information and the delayed remote information, i.e.,

$$T_1(t) := T_1\left(q_1(t), \dot{q}_1(t), q_2(t-\tau_2), \dot{q}_2(t-\tau_2)\right) \in \Re^n \quad (4)$$
$$T_2(t) := T_2\left(q_2(t), \dot{q}_2(t), q_1(t-\tau_1), \dot{q}_1(t-\tau_1)\right) \in \Re^n. \quad (5)$$

B. Control Objectives

We would like to design the controls $T_1(t)$, $T_2(t)$ in (4) and (5) to achieve: *master–slave position coordination*: if $(F_1(t), F_2(t)) = 0$

$$q_E(t) := q_1(t) - q_2(t) \to 0, \quad t \to \infty \quad (6)$$

and 2) *static force reflection*: with $(\ddot{q}_1(t), \ddot{q}_2(t), \dot{q}_1(t), \dot{q}_1(t)) \to 0$

$$F_1(t) \to -F_2(t). \quad (7)$$

For the safe interaction and coupled stability, we would also like to enforce the following *energetic passivity* of the closed-loop teleoperator (1) and (2): there exists a finite constant $d \in \Re$ s.t.

$$\int_0^t \left[F_1^T(\theta)\dot{q}_1(\theta) + F_2^T(\theta)\dot{q}_2(\theta)\right] d\theta \geq -d^2 \quad \forall t \geq 0 \quad (8)$$

i.e., maximum extractable energy from the two-port closed-loop teleoperator is always bounded (see Fig. 1). Let us also define *controller passivity* [10], [11], [23]: there exists a finite constant $c \in \Re$ s.t.

$$\int_0^t \left[T_1^T(\theta)\dot{q}_1(\theta) + T_2^T(\theta)\dot{q}_2(\theta)\right] d\theta \leq c^2 \quad \forall t \geq 0 \quad (9)$$

i.e., energy generated by the two-port controller (see Fig. 1) is always limited.

Lemma 1 [11], [23]: For the mechanical teleoperator (1) and (2), controller passivity (9) implies energetic passivity (8).

Proof: Let us define the total kinetic energy

$$\kappa_f(t) := \frac{1}{2}\dot{q}_1^T(t)M_1(q_1)\dot{q}_1(t) + \frac{1}{2}\dot{q}_2^T(t)M_2(q_2)\dot{q}_2(t) \quad (10)$$

then, using the dynamics (1) and (2) and its skew-symmetric property, we have

$$\frac{d}{dt}\kappa_f(t) = T_1^T(t)\dot{q}_1(t) + T_2^T(t)\dot{q}_2(t) + F_1^T(t)\dot{q}_1(t) + F_2^T(t)\dot{q}_2(t). \quad (11)$$

Thus, integrating (11) with the controller passivity (9) and the fact that $\kappa_f(t) \geq 0$, we have $\forall t \geq 0$

$$\int_0^t \left[F_1^T(\theta)\dot{q}_1(\theta) + F_2^T(\theta)\dot{q}_2(\theta)\right] d\theta \geq -\kappa_f(0) - c^2 =: -d^2.$$

■

Lemma 1 is simple but powerful, in the sense that it enables us to analyze energetic passivity (8) of the closed-loop teleoperator by examining only the controller structure, which is often much simpler than that of the closed-loop dynamics. Furthermore, by enforcing controller passivity (9), energetic passivity (8) will be guaranteed robustly (robust passivity [11], [23]), because controller passivity (9) does not depend on the possibly uncertain open-loop dynamics (1) and (2).

III. Control Design

In order to achieve master–slave coordination (6), bilateral force reflection (7), and energetic passivity (8) of the closed-loop teleoperator, we design the master and slave controls $T_1(t)$, $T_2(t)$ in (4) and (5) to be

$$T_1(t) := \underbrace{-K_v\left(\dot{q}_1(t) - \dot{q}_2(t-\tau_2)\right)}_{\text{delayed D-action}} \underbrace{-(K_d + P_\epsilon)\dot{q}_1(t)}_{\text{dissipation}} \underbrace{-K_p\left(q_1(t) - q_2(t-\tau_2)\right)}_{\text{delayed P-action}} \quad (12)$$

$$T_2(t) := \underbrace{-K_v\left(\dot{q}_2(t) - \dot{q}_1(t-\tau_1)\right)}_{\text{delayed D-action}} \underbrace{-(K_d + P_\epsilon)\dot{q}_2(t)}_{\text{dissipation}} \underbrace{-K_p\left(q_2(t) - q_1(t-\tau_1)\right)}_{\text{delayed P-action}} \quad (13)$$

where $\tau_1,\ \tau_2 \geq 0$ are the forward and backward finite constant communication delays, $K_v,\ K_p \in \Re^{n \times n}$ are the symmetric and positive-definite PD control gains, $K_d \in \Re^{n \times n}$ is the dissipation gain to passify the delayed P-control action (to be designed below), and $P_\epsilon \in \Re^{n \times n}$ is an additional damping ensuring master–slave coordination (6). Inherent device viscous damping can substitute this additional damping P_ϵ. Note that the control laws (12) and (13) require the communication of both the position and velocity signals. Such an explicit position feedback is generally absent in the conventional scattering-based teleoperation.

To enforce energetic passivity (8), we design the dissipation gain K_d in (12) and (13) to satisfy the following condition:

$$K_d \succcurlyeq \left[\frac{\sin\frac{w(\tau_1+\tau_2)}{2}}{w}\right]^2 K_p K_d^{-1} K_p \quad \forall w \in \Re \tag{14}$$

where, for square matrices A, B, $A \succcurlyeq B$ implies that $A-B$ is positive-semidefinite. As to be shown below, with this condition (14), the delayed P-control action (i.e., with K_p) can be passified by the dissipation K_d. From the fact that $\tau - (\sin w\tau/w) \geq 0\, \forall w \in \Re$, one possible solution for the condition (14) can be given by

$$K_d = \frac{\bar{\tau}_{rt}}{2} K_p \tag{15}$$

where $\bar{\tau}_{rt} \geq 0$ is an upper bound of the round-trip delay $\tau_{rt} := \tau_1 + \tau_2$ s.t. $\bar{\tau}_{rt} \geq \tau_{rt}$.

The proposed control law (12) and (13) under the condition (14) ensures energetic passivity (8) of the closed-loop teleoperator, the master–slave position coordination (6), and the static bilateral force reflection (7) as summarized by the following theorem.

Theorem 1: Consider the mechanical teleoperator (1) and (2) under the controls (12) and (13) satisfying the condition (14).

1) (Robust Passivity) The closed-loop teleoperator under the controls (12) and (13) is energetically passive, i.e., satisfies (8), regardless of parametric uncertainty in the open-loop dynamics (1), (2).
2) (Coupled Stability) Suppose that the human operator and slave environment in Fig. 1 define passive mappings with their respective mechanical power inflow as their supply rate [2]: i.e., $\exists$ finite constants $d_1, d_2 \in \Re$ s.t.
$$\int_0^t -F_i^T(\theta)\dot{q}_i(\theta)d\theta \geq -d_i^2 \quad \forall t \geq 0 \tag{16}$$
$i = 1, 2$, i.e., maximum extractable energy from the human operator and slave environment are bounded. Then, $\dot{q}_1(t), \dot{q}_2(t) \in \mathcal{L}_\infty$. Therefore, if the human operator and slave environment are $\mathcal{L}_\infty$-stable input–output impedance maps, $F_1(t), F_2(t) \in \mathcal{L}_\infty$.
3) (Position Coordination) Suppose that the human operator and slave environment are passive in the sense of (16). Then, the coordination error $q_E(t) = q_1(t) - q_2(t)$ in (6) is bounded $\forall t \geq 0$. Suppose further that $M_i^{jk}(q_i)$, $\partial M_i^{jk}(q_i)/\partial q_i^m$ and $\partial^2 M_i^{jk}(q_i)/\partial q_i^m \partial q_i^l$ are all bounded for every q_i, where $M_i^{jk}(q_i)$ and q_i^m are the jkth and the mth components of the inertia matrix $M_i(q_i)$ and the configuration q_i, respectively. Then, if $(F_1(t), F_2(t)) = 0\, \forall t \geq 0$, $(q_E(t), \dot{q}_E(t)) \to 0$ (i.e., (6) is achieved).
4) (Force Reflection) If $(\dot{q}_1(t), \dot{q}_2(t), \ddot{q}_1(t), \ddot{q}_2(t)) \to 0$, $F_1(t) \to -F_2(t) \to -K_p(q_1(t) - q_2(t))$, i.e., (7) is achieved.

Proof: **1)** Let us denote the mechanical power generated by the controls (12) and (13) by

$$\begin{aligned} s_c(t) &:= T_1^T(t)\dot{q}_1(t) + T_2^T(t)\dot{q}_2(t) \\ &= s_d(t) + s_p(t) - P(t) \end{aligned} \tag{17}$$

where $s_d(t)$ and $s_p(t)$ are the supply rates associated with the delayed D-action and the delayed P-action (+ dissipation K_d), respectively, and defined by

$$\begin{aligned} s_d(t) := &-\dot{q}_1^T(t)K_v\dot{q}_1(t) + \dot{q}_1^T(t)K_v\dot{q}_2(t-\tau_2) \\ &- \dot{q}_2^T(t)K_v\dot{q}_2(t) + \dot{q}_2^T(t)K_v\dot{q}_1(t-\tau_1) \end{aligned} \tag{18}$$

$$\begin{aligned} s_p(t) := &-\dot{q}_1^T(t)K_d\dot{q}_1(t) - \dot{q}_2^T(t)K_d\dot{q}_2(t) \\ &- \dot{q}_1^T(t)K_p\left(q_1(t) - q_2(t-\tau_2)\right) \\ &- \dot{q}_2^T(t)K_p\left(q_2(t) - q_1(t-\tau_1)\right) \end{aligned} \tag{19}$$

and $P(t)$ is the following positive-definite quadratic form:

$$P(t) := \begin{pmatrix} \dot{q}_1(t) \\ \dot{q}_2(t) \end{pmatrix}^T \begin{bmatrix} P_\epsilon & 0 \\ 0 & P_\epsilon \end{bmatrix} \begin{pmatrix} \dot{q}_1(t) \\ \dot{q}_2(t) \end{pmatrix}. \tag{20}$$

We want the total controller supply rate $s_c(t)$ in (17) to satisfy the controller passivity (9).

Let us first consider the delayed D-action supply rate $s_d(t)$ in (18). Then, using the fact that

$$2\dot{q}_i^T(t)K_v\dot{q}_k(t-\tau_k) \leq \dot{q}_i^T(t)K_v\dot{q}_i(t) + \dot{q}_k^T(t-\tau_k)K_v\dot{q}_k(t-\tau_k) \tag{21}$$

$(i,k) = \{(1,2),(2,1)\}$, we can show that

$$\begin{aligned} s_d(t) \leq &-\frac{1}{2}\left[\dot{q}_1^T(t)K_v\dot{q}_1(t) - \dot{q}_1^T(t-\tau_1)K_v\dot{q}_1(t-\tau_1)\right] \\ &-\frac{1}{2}\left[\dot{q}_2^T(t)K_v\dot{q}_2(t) - \dot{q}_2^T(t-\tau_2)K_v\dot{q}_2(t-\tau_2)\right] \\ = &-\frac{d}{dt}V_v(t) \end{aligned} \tag{22}$$

where $V_v(t)$ is a Lyapunov–Krasovskii functional for delayed systems [24] defined by

$$\begin{aligned} V_v(t) := &\frac{1}{2}\int_{-\tau_1}^0 \dot{q}_1^T(t+\theta)K_v\dot{q}_1(t+\theta)d\theta \\ &+ \frac{1}{2}\int_{-\tau_2}^0 \dot{q}_2^T(t+\theta)K_v\dot{q}_2(t+\theta)d\theta \geq 0. \end{aligned} \tag{23}$$

Then, by integrating the inequality (22), we have

$$\int_0^t s_d(\theta)d\theta \leq -V_v(t) + V_v(0) \tag{24}$$

i.e., energy generation by the delayed D-action is always bounded by the energy stored in the Lyapunov–Krasovskii functional $V_v(t)$ (i.e., $V_v(t)$ is the storage function for the supply rate $s_d(t)$).

Now, let us consider the supply rate $s_p(t)$ in (19). Then, we can rewrite $s_p(t)$ in (19) s.t.

$$\begin{aligned} s_p(t) = &-\dot{q}_1^T(t)K_d\dot{q}_1(t) - \dot{q}_2^T(t)K_d\dot{q}_2(t) \\ &- \dot{q}_1^T(t)K_p\left(q_1(t) - q_2(t)\right) \\ &- \dot{q}_1^T(t)K_p\left(q_2(t) - q_2(t-\tau_2)\right) \\ &- \dot{q}_2^T(t)K_p\left(q_2(t) - q_1(t)\right) \\ &- \dot{q}_2^T(t)K_p\left(q_1(t) - q_1(t-\tau_1)\right) \\ = &-\frac{d}{dt}V_p(t) - \dot{q}_1^T(t)K_d\dot{q}_1(t) - \dot{q}_2^T(t)K_d\dot{q}_2(t) \\ &- \dot{q}_1^T(t)K_p\left(q_2(t) - q_2(t-\tau_2)\right) \\ &- \dot{q}_2^T(t)K_p\left(q_1(t) - q_1(t-\tau_1)\right) \end{aligned} \tag{25}$$

where $V_p(t)$ is the potential energy stored in the P-action spring, i.e.,

$$V_p(t) := \frac{1}{2} q_E^T(t) K_p q_E(t) \tag{26}$$

with $q_E(t) = q_1(t) - q_2(t)$ as defined in (6). As in [33], let us define the truncated signal $\tilde{\dot{q}}_i^t(\theta)$ of $\dot{q}_i(t)$ s.t. for $i = 1, 2$

$$\tilde{\dot{q}}_i^t(\theta) := \begin{cases} \dot{q}_i(\theta), & \text{if } \theta \in [0, t] \\ 0, & \text{otherwise.} \end{cases} \tag{27}$$

Then, the energy generation by the supply rate $s_p(t)$ in (25) can be written as

$$\begin{aligned}
\int_0^t s_p(\theta) d\theta &= -V_p(t) + V_p(0) - \int_{-\infty}^{+\infty} \tilde{\dot{q}}_1^{tT}(\theta) K_d \tilde{\dot{q}}_1^t(\theta) d\theta \\
&\quad - \int_{-\infty}^{+\infty} \tilde{\dot{q}}_2^{tT}(\theta) K_d \tilde{\dot{q}}_2^t(\theta) d\theta \\
&\quad - \int_{-\infty}^{+\infty} \tilde{\dot{q}}_1^{tT}(\theta) K_p \underbrace{\left[\int_{-\infty}^{\theta} \tilde{\dot{q}}_2^t(\xi) d\xi - \int_{-\infty}^{\theta-\tau_2} \tilde{\dot{q}}_2^t(\xi) d\xi \right]}_{:= g_2^t(\theta)} d\theta \\
&\quad - \int_{-\infty}^{+\infty} \tilde{\dot{q}}_2^{tT}(\theta) K_p \underbrace{\left[\int_{-\infty}^{\theta} \tilde{\dot{q}}_1^t(\xi) d\xi - \int_{-\infty}^{\theta-\tau_1} \tilde{\dot{q}}_1^t(\xi) d\xi \right]}_{:= g_1^t(\theta)} d\theta.
\end{aligned} \tag{28}$$

Let us denote the Fourier transform of $\tilde{\dot{q}}_i^t$ ($i = 1, 2$) by $V_i^t(w) := \int_{-\infty}^{+\infty} \tilde{\dot{q}}_i^t(\theta) e^{-jw\theta} d\theta = \int_0^t \dot{q}_i(\theta) e^{-jw\theta} d\theta$, where $j = \sqrt{-1}$. Then, as shown in Appendix A, the Fourier transform of $g_i^t(\theta)$ in (28) (i.e., $G_i^t(w) := \int_{-\infty}^{+\infty} g_i^t(\theta) e^{-jw\theta} d\theta$) is given by $G_i^t(w) = ((1 - e^{-jw\tau_i})/jw) V_i^t(w)$. Let us denote the complex conjugate transpose of a complex vector $\star \in \mathbb{C}^n$ by $\star^*$ (i.e., $\star^* = \bar{\star}^T$). Then using Parseval's identity [25], the equality (28) can be rewritten as

$$\begin{aligned}
\int_0^t s_p(\theta) d\theta &= -V_p(t) + V_p(0) - \frac{1}{2\pi} \int_{-\infty}^{+\infty} V_1^{t*}(w) K_d V_1^t(w) dw \\
&\quad - \frac{1}{2\pi} \int_{-\infty}^{+\infty} V_2^{t*}(w) K_d V_2^t(w) dw \\
&\quad - \frac{1}{2\pi} \int_{-\infty}^{+\infty} V_1^{t*}(w) K_p \frac{1 - e^{-jw\tau_2}}{jw} V_2^t(w) dw \\
&\quad - \frac{1}{2\pi} \int_{-\infty}^{+\infty} V_2^{t*}(w) K_p \frac{1 - e^{-jw\tau_1}}{jw} V_1^t(w) dw \\
&= -V_p(t) + V_p(0) \\
&\quad - \frac{1}{2\pi} \int_{-\infty}^{+\infty} \begin{pmatrix} \bar{V}_1^t(w) \\ \bar{V}_2^t(w) \end{pmatrix}^T H(w) \begin{pmatrix} V_1^t(w) \\ V_2^t(w) \end{pmatrix} dw
\end{aligned} \tag{29}$$

where, following the derivations in Appendix B, $H(w) \in \mathbb{C}^{2n \times 2n}$ is given by

$$H(w) = \begin{bmatrix} K_d & \frac{K_p}{2} \frac{e^{jw\tau_1} - e^{-jw\tau_2}}{jw} \\ \frac{K_p}{2} \frac{e^{jw\tau_2} - e^{-jw\tau_1}}{jw} & K_d \end{bmatrix}.$$

Since $H(w)$ is Hermitian with positive-definite block diagonal matrices K_d, following [34, pp. 473], $H(w) \succcurlyeq 0$ (i.e., $H(w)$ is positive-semidefinite) if and only if

$$\begin{aligned}
K_d &\succcurlyeq \frac{e^{jw\tau_1} - e^{-jw\tau_2}}{2jw} \frac{e^{jw\tau_2} - e^{-jw\tau_1}}{2jw} K_p K_d^{-1} K_p \\
&= \frac{1 - \cos w(\tau_1 + \tau_2)}{2w^2} K_p K_d^{-1} K_p
\end{aligned} \tag{30}$$

which is nothing but the condition (14), because $1 - \cos w(\tau_1 + \tau_2) = 2(\sin(w(\tau_1 + \tau_2)/2))^2$. Thus, with the condition (14) s.t. $H(w) \succcurlyeq 0$, we can show from (29) that

$$\int_0^t s_p(\theta) d\theta \leq -V_p(t) + V_p(0) \tag{31}$$

i.e., energy generation by the supply rate $s_p(t)$ is always bounded by the P-action spring energy $V_p(t)$ in (26).

Thus, by combining (17), (24), and (31) with the fact that $V_v(t) \geq 0$ and $V_p(t) \geq 0 \; \forall t \geq 0$, and $P(t)$ in (20) is a positive-definite quadratic form, we can prove controller passivity (9) s.t. $\forall t \geq 0$

$$\begin{aligned}
\int_0^t \left[T_1^T(\theta) \dot{q}_1(\theta) + T_2^T(\theta) \dot{q}_2(\theta) \right] d\theta &= \int_0^t [s_d(\theta) + s_p(\theta)] d\theta - \int_0^t P(\theta) d\theta \\
&\leq -V_v(t) + V_v(0) - V_p(t) + V_p(0) \\
&\leq V_v(0) + V_p(0) =: c^2
\end{aligned} \tag{32}$$

where the term $V_v(0)$ will be zero if we start from zero velocities (i.e., $(\dot{q}_1(t), \dot{q}_2(t)) = 0 \; \forall t \in (-\infty, 0]$), while the term $V_p(0)$ would be small, if the initial coordination error $q_E(0) = q_1(0) - q_2(0)$ is small. Finally, from *Lemma 1*, energetic passivity (8) of the closed-loop teleoperator follows.

2) By integrating the equality (11) with the inequality (32) and the energetic passivity of the human and slave environment (16), we have, for all $t \geq 0$

$$\begin{aligned}
\kappa_f(t) + V_v(t) + V_p(t) &\leq \kappa_f(0) + V_v(0) + V_p(0) \\
&\quad - \int_0^t P(\theta) d\theta + d_1^2 + d_2^2.
\end{aligned} \tag{33}$$

Here, since $V_v(0)$, $V_p(0)$, d_1^2, d_2^2, and $\kappa_f(0)$ are all bounded, $\kappa_f(t)$ is bounded. Thus, $\dot{q}_1(t)$, $\dot{q}_2(t)$ are also bounded $\forall t \geq 0$ (i.e., $\dot{q}_1(t), \dot{q}_2(t) \in \mathcal{L}_\infty$). Therefore, if the human operator and the slave environment are $\mathcal{L}_\infty$-stable impedance maps, $F_1(t)$, $F_2(t) \in \mathcal{L}_\infty$.

3) Boundedness of $q_E(t) = q_1(t) - q_2(t)$ is a direct consequence of the inequality (33) and the definition of $V_p(t)$ in (26).

The first step of the position-coordination proof is to show that $(\dot{q}_1(t), \dot{q}_2(t)) \to 0$. Suppose that $(F_1(t), F_2(t)) = 0\ \forall t \geq 0$. Then, from (33) with $d_1 = d_2 = 0$ and the boundedness of P_ϵ, $M_1(q_1)$, $M_2(q_2)$, we have $\forall t \geq 0$

$$\begin{aligned}\kappa_f(t) &\leq \kappa_f(0) + c^2 - \int_0^t P(\theta)d\theta \\ &\leq \kappa_f(0) + c^2 - \gamma \int_0^t \kappa_f(\theta)d\theta \end{aligned} \tag{34}$$

where $c^2 = V_v(0) + V_p(0)$ as given in (32), and $\gamma > 0$ is a constant scalar s.t. $P(t) \geq \gamma \kappa_f(t)$. Such a γ always exists, because $P(t)$ in (20) and $\kappa_f(t)$ in (10) are both positive-definite quadratic form with respect to (w.r.t.) $\dot{q}_1(t)$ and $\dot{q}_2(t)$. Here, since $\kappa_f(t) \geq 0$, the term $\int_0^t \kappa_f(\theta)d\theta$ is monotonically increasing and upper bounded, thus, it converges to a limit. Therefore, following Barbalat's lemma [35], if $\kappa_f(t)$ is uniformly continuous, $\kappa_f(t)$ will also converge to 0 (i.e., $(\dot{q}_1(t), \dot{q}_2(t)) \to 0$). To show this, let us consider $d\kappa_f(t)/dt$. Then, from (11) with $F_1(t) = F_2(t) = 0$, we have $d\kappa_f(t)/dt = T_1^T(t)\dot{q}_1(t) + T_2^T(t)\dot{q}_2(t)$, where $\dot{q}_1(t)$, $\dot{q}_2(t)$ are bounded from item 2 of this theorem. Also, $T_1(t)$, $T_2(t)$ are bounded, since, in their definitions (12) and (13), for $(i,k) = \{(1,2),(2,1)\}$, $\dot{q}_i(t) - \dot{q}_k(t - \tau_k)$ is bounded (with bounded $\dot{q}_i(t)$), and $q_i(t) - q_k(t - \tau_k) = q_E(t) + \int_{-\tau_k}^0 \dot{q}_k(t+\theta)d\theta$ is also bounded (with bounded $q_E(t)$, $\dot{q}_i(t)$, and τ_k). Thus, $d\kappa_f(t)/dt$ is bounded, and $\kappa_f(t)$ is uniformly continuous. Therefore, $\kappa_f(t) \to 0$ and $(\dot{q}_1(t), \dot{q}_2(t)) \to 0$.

The next step of the proof is to show that $(\ddot{q}_1(t), \ddot{q}_2(t)) \to 0$ to establish $q_1(t) \to q_2(t)$. Let us consider the teleoperator dynamics (1) and (2) with $F_1(t) = F_2(t) = 0$, where, as shown in the previous paragraph, the controls $T_1(t)$, $T_2(t)$ in (12) and (13) are bounded. Also, from the boundedness assumption of $\partial M_i^{jk}(q_i)/\partial q_i^m$, the Coriolis terms $C_i(q_i, \dot{q}_i)\dot{q}_i$ $(i = 1,2)$ in (1) and (2) are bounded. Thus, the accelerations $\ddot{q}_1(t)$, $\ddot{q}_2(t)$ are also bounded $\forall t \geq 0$. Now, let us consider the acceleration $\ddot{q}_i(t)$ in (1) and (2) (with $F_i(t) = 0$)

$$\ddot{q}_i = -M_i^{-1}(q_i)C_i(q_i, \dot{q}_i)\dot{q}_i + M_i^{-1}(q_i)T_i(t) \tag{35}$$

$i = 1,2$, where the time derivatives of the terms in the right-hand side (RHS) are all bounded, due to the boundedness of $\ddot{q}_i(t)$, $\dot{q}_i(t)$, $q_E(t)$, $(d/dt)M_i^{-1}(q_i) = -M_i^{-1}(q_i)(d/dt)M_i(q_i)M_i^{-1}(q_i)$ (from the boundedness assumption on $\partial M_i^{jk}(q_i)/\partial q_i^m$), and $(d/dt)C_i(q_i, \dot{q}_i)\dot{q}_i$ (from the boundedness assumption on $\partial^2 M_i^{jk}(q_i)/\partial q_i^m \partial q_i^l$). This implies that the RHS of (35) is uniformly continuous. Thus, $\ddot{q}_1(t)$, $\ddot{q}_2(t)$ are also uniformly continuous. Therefore, following Barbalat's lemma [35], $(\ddot{q}_1(t), \ddot{q}_2(t)) \to 0$ as $(\dot{q}_1(t), \dot{q}_2(t) \to 0$.

Now, let us consider the dynamics (1) and (2) with the controls $T_1(t)$, $T_2(t)$ in (12) and (13) and $F_1(t) = F_2(t) = 0$. Then, since $(\ddot{q}_1(t), \ddot{q}_2(t), \dot{q}_1(t), \dot{q}_2(t)) \to 0$, we have $K_p(q_i(t) - q_k(t - \tau_k)) \to 0$, $(i,k) = \{(1,2),(2,1)\}$. This condition can be rewritten as $K_p(q_E(t) + \int_{-\tau_k}^0 \dot{q}_k(t+\theta)d\theta) \to 0$, where the second term in the left-hand side goes to zero, as $\dot{q}_k(t) \to 0$ and τ_k is finite. Therefore, since K_p is positive-definite, $q_E(t) \to 0$ (i.e., $q_1(t) \to q_2(t)$).

4) Suppose that $(\dot{q}_1(t), \dot{q}_2(t), \ddot{q}_1(t), \ddot{q}_2(t)) \to 0$. Then, from the teleoperator dynamics (1) and (2) and their controls (12) and (13), we have

$$\begin{aligned} F_1(t) &\to -K_p\,(q_1(t) - q_2(t)) \\ F_2(t) &\to -K_p\,(q_2(t) - q_1(t)) \end{aligned} \tag{36}$$

where $\dot{q}_i(t - \tau) \to 0$ and $q_i(t - \tau) \to q_i(t)$ as $(\dot{q}_1(t), \dot{q}_2(t), \ddot{q}_1(t), \ddot{q}_2(t)) \to 0$. ■

In *Theorem 1*, the negative signs in the passivity condition for the human and slave environment (16) come from the fact that the power inflows to those systems are given by $(-F_i(t))^T \dot{q}_i(t)$, i.e., the product of the reaction force $-F_i(t)$ and the interaction velocity $\dot{q}_i(t)$. The boundedness assumption on $M_i^{jk}(q_i)$, $\partial M_i^{jk}(q_i)/\partial q_i^m$ and $\partial^2 M_i^{jk}(q_i)/\partial q_i^m \partial q_i^l$ in item 3 of *Theorem 1* will be guaranteed, if the master and slave configuration spaces are compact and their respective inertia matrices are smooth. Such compact configuration space and smooth inertia are possessed by many practical robotic systems (e.g., revolute joint robots).

The condition (15) [or (14)] enables us to passify the delayed P-action in (12) and (13) by the dissipation K_d. This delayed P-action contains an explicit position feedback information, the lack of which is recognized as the main cause of the master–slave position drift in the conventional scattering-based teleoperation. In contrast, the delayed D-action in (12) and (13) is itself passive, with the Lyapunov–Krasovskii function $V_v(t)$ in (23) as its storage function (see the proof of item 1). Since the condition (15) can be achieved as long as the delays τ_1, τ_2 are finite constants and their round-trip delay (i.e., $\tau_1 + \tau_2$) is upper bounded, energetic passivity (8) can also be ensured with such finite constant delays, even if they are not exactly known or they are asymmetric (i.e., $\tau_1 \neq \tau_2$).

Notice from item 4 of *Theorem 1* that the P-action gain K_p in (12) and (13) determines the (static) force-reflection performance, as it specifies how much force is generated for a given master–slave position error. Note also that a large dissipation gain K_d in (12) and (13) would make the system response sluggish. Therefore, the condition (15) imposes the following implications on the system performance: 1) with the same force-reflection performance (i.e., same K_p), the motion agility (i.e., less K_d) would be compromised as the delays becomes longer, since in the condition (15), the required dissipation K_d is proportional to the round-trip delay τ_{rt}; and 2) with the same delay τ_{rt}, there is a tradeoff between the force-reflection performance and motion agility, since under the condition (15), a large K_p (i.e., sharp force reflection) requires a large K_d (i.e., poor motion agility), or a small K_d (i.e., agile free motion) permits only a small K_p (i.e., poor force reflection).

The key step in the proof of *Theorem 1* is the use of Parseval's identity in (29). A sufficient condition for Parseval's identity to hold is that $\dot{q}_1(t)$, $\dot{q}_2(t) \in \mathcal{L}_2$ [25]. As the following lemma shows, this sufficient condition is guaranteed in many practical situations where the human and slave environment are passive in the sense of (16), the Christoffel symbols of the master and the slave robots (1) and (2) are bounded, and the master and slave velocities and the coordination error are initially bounded. Parseval's identity was also used in [33] to ensure the energetic passivity of haptic interfaces under zero-order-hold.

Lemma 2: Suppose that the human and slave environment are passive in the sense of (16), and define $\mathcal{L}_\infty$-stable impedance maps (i.e., if $\dot{q}_1(t), \dot{q}_2(t) \in \mathcal{L}_\infty$, $F_1(t), F_2(t) \in \mathcal{L}_\infty$). Suppose further that Christoffel's symbols ${}^i\Gamma^j_{km}(q_i)$ in the Coriolis matrices (3) are bounded $\forall q_i$ ($i = 1, 2$, $j, k, m = 1, \ldots, n$). Then, if $\dot{q}_1(0)$, $\dot{q}_2(0)$, $q_E(0)$ are bounded, $\dot{q}_1(t)$, $\dot{q}_2(t) \in \mathcal{L}_2$, thus, Parseval's identity in (29) holds, and items 1–3 of *Theorem 1* requiring Parseval's identity (29) are ensured.

Proof: Suppose that $\dot{q}_1(t)$, $\dot{q}_2(t)$, $q_E(t)$ are bounded. Then, the controls $T_1(t)$, $T_2(t)$ are bounded (as shown in the proof of item 3 of *Theorem 1*) and $F_1(t)$, $F_2(t)$ are bounded (from the $\mathcal{L}_\infty$-stable impedance map assumption). Thus, from the dynamics (1) and (2) with bounded Christoffel's symbols ${}^i\Gamma^j_{km}(q_i)$ in (3), $\ddot{q}_1(t)$, $\ddot{q}_2(t)$ are also bounded. Therefore, with the bounded $\dot{q}_1(0)$, $\dot{q}_2(0)$, $q_E(0)$ (thus, $\ddot{q}_1(0)$, $\ddot{q}_2(0)$ are also bounded), we can find an interval $\bar{I} := [0, \bar{t})$ with $\bar{t}$ being a strictly positive scalar s.t. $\forall t \in \bar{I}$

$$\int_0^t P(\theta)d\theta < \bar{M} \tag{37}$$

where $P(t)$ is defined in (20), and $\bar{M}$ is a sufficiently large positive scalar. Thus, on the interval $\bar{I}$, Parseval's identity (29) holds, and following the inequality (33), $\dot{q}_1(t)$, $\dot{q}_2(t)$, $q_E(t)$ are all bounded.

Suppose that $\dot{q}_1(t) \notin \mathcal{L}_2$ or $\dot{q}_2(t) \notin \mathcal{L}_2$. Then, from the fact that $\int_0^t P(\theta)d\theta$ is continuous on $\bar{I}$ (since $\dot{q}_1(t)$, $\dot{q}_2(t)$ are bounded $\forall t \in \bar{I}$) and monotonically increasing $\forall t \geq 0$ (since $P(t)$ in (20) is positive-definite), there should exist a time $0 < t_o < \bar{t}$ s.t.

$$M < \int_0^{t_o} P(\theta)d\theta < \bar{M} \tag{38}$$

where we define $M := \kappa_f(0) + V_v(0) + V_p(0) + d_1^2 + d_2^2 + \epsilon$ with $\epsilon > 0$ being a (small) strictly positive scalar. However, this is not possible, since, on the interval $\bar{I}$, Parseval's identity (29) holds, thus, from (33), we have

$$\begin{aligned} 0 &\leq \kappa_f(t) + V_v(t) + V_p(t) \\ &\leq \underbrace{\kappa_f(0) + V_v(0) + V_p(0) + d_1^2 + d_2^2}_{<M} - \int_0^t P(\theta)d\theta \end{aligned} \tag{39}$$

for all $t \in \bar{I}$, i.e., $\int_0^t P(\theta)d\theta < M$ $\forall t \in \bar{I}$. This inequality (39) implies that, with bounded initial velocities $(\dot{q}_1(0), \dot{q}_2(0))$ and coordination error $q_E(0)$, $\int_0^t P(\theta)d\theta$ in (37) will be uniformly bounded by M and cannot blow up. Thus, $\dot{q}_1(t), \dot{q}_2(t) \in \mathcal{L}_2$, therefore, following [25], Parseval's identity (29) is valid $\forall t \geq 0$. ∎

IV. Simulation and Experiment

A. Simulation

In this simulation, we consider a pair of 2-serial-links revolute-joint direct-drive planar robots. Then, following a standard textbook as [32], their joint-space inertia matrices $M_i(q_i) \in \Re^{2\times 2}$ ($i = 1$: master, $i = 2$: slave) share the following positive-definite and symmetric structure: $(M_i^{11}(q_i), M_i^{12}(q_i), M_i^{22}(q_i)) = (\alpha_i + 2\beta_i c2, \delta_i + \beta_i c2, \delta_i)$ with $M_i^{12}(q_i) = M_i^{21}(q_i)$, where $M_i^{jk}(q_i)$ is the jkth component of $M_i(q_i)$ ($j, k = 1, 2$) and $c2$ is the cosine of the distal link angle w.r.t. the proximal link. We choose $(\alpha_1, \beta_1, \delta_1) := (0.75, 0.063, 0.09)$ kgm^2 for the master and $(\alpha_2, \beta_2, \delta_2) := (0.56, 0.046, 0.086)$ kgm^2 for the slave. We also set the lengths of the proximal and distal links of both the master and slave robot to be the same as (38 cm, 38 cm). These kinematic and dynamic parameters are adapted from those of the slave robot in [11], with the inertia being reduced by approximately one-third and the proximal link being slightly lengthened. For more details on the real robot, refer to [11].

We model the human operator as a PD-type position-tracking controller (i.e., spring and damper) with its spring and damping gains as 75 N/m and 50 Ns/m for both x and y directions. These gains are chosen assuming that the human positions the master robot without overshoots. To evaluate the contact stability, we implement a wall in the slave environment at $x = 35$ cm, modeled as a lightly damped spring-damper system (with the spring and damping gains being 500 N/m and 0.1 Ns/m) reacting only along the x direction.

We derive the controller in (12) and (13) w.r.t. the Cartesian space dynamics (i.e., q_1, q_2 in (1) and (2) being the Cartesian (x, y) positions) so that, with item 4 of *Theorem 1*, the Cartesian force (i.e., end-tip (x, y) force) can be reflected.[1] As a simulation platform, we use MatLab SimuLink (The MathWorks Inc., Natick, MA) with a 0.02 s update rate.

We consider the following scenario. At the beginning 0–50 s, the human operator stabilizes the master at $(x, y) = (17.5, 0)$ cm; then, at 50–150 s, the human pushes the master to the position $(x, y) = (52.5, 0)$ cm to make a hard contact (i.e., maintains the pushing force with negligible velocity/acceleration) between the slave and the wall; finally, at 150–250 s, the human retracts the master to the original position $(x, y) = (17.5, 0)$ cm.

The following two sets of the delays are assumed: $(\tau_1, \tau_2) = (0.4, 0.6)$ s (i.e., round-trip delay $\tau_{rt} = 1$ s) and $(\tau_1, \tau_2) = (1.2, 1.8)$ s (i.e., $\tau_{rt} = 3.0$ s). For these two sets, we choose the P-action gain K_p in (12) and (13) to be $50 I_{2\times 2}$ N/m. Then, the dissipation gain K_d in (12) and (13) is chosen according to (15): $K_d = 25 I_{2\times 2}$ for $\tau_{rt} = 1$ s, and $K_d = 75 I_{2\times 2}$ for $\tau_{rt} = 3$ s. The extra damping P_ϵ and the D-action gain K_v in (12) and (13) are also set to be $0.001 K_d$ and $I_{2\times 2}$, respectively. Simulation results with these two delay sets are given in Figs. 2 and 3, respectively. Only the x axis position and force are presented in the figures, as they are dominant over those in the y axis.

As shown in Figs. 2 and 3, when the slave robot is pushing against the wall with small velocity and acceleration (100–150 s), the contact force is faithfully reflected to

[1]However, since the master and slave robots are kinematically identical in this simulation, the Cartesian force reflection also implies joint-torque reflection.

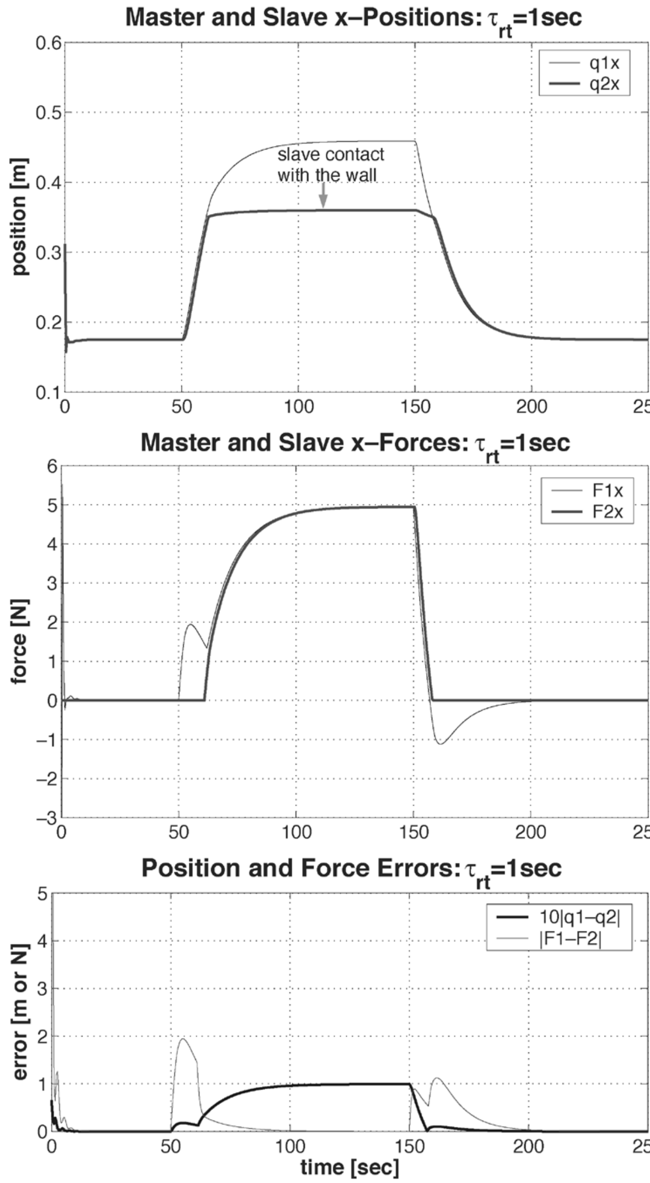

Fig. 2. Simulation result: $\tau_{rt} = 1$ s, $K_p = 50I_{2\times 2}$, $K_d = 25I_{2\times 2}$.

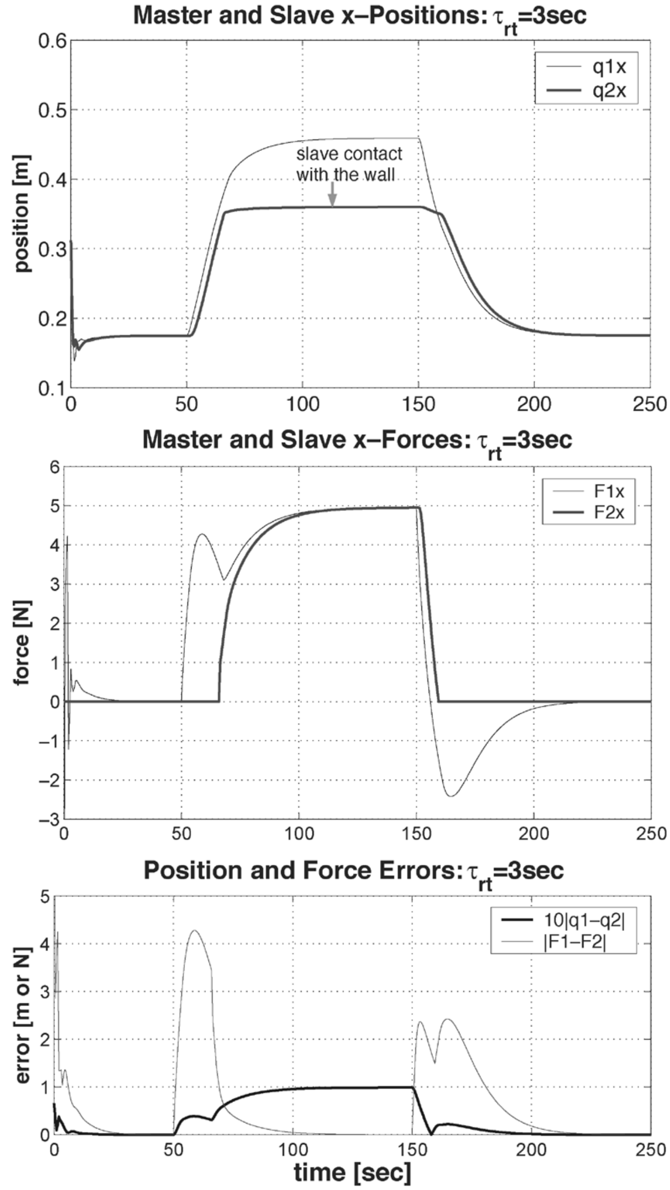

Fig. 3. Simulation result: $\tau_{rt} = 3$ s, $K_p = 50I_{2\times 2}$, $K_d = 75I_{2\times 2}$.

the human operator via the P-action K_p in (12) and (13). Also, when the slave does not interact with the wall and the human forcing is negligible (e.g., 20–50 s and 220–250 s), the master–slave position coordination is achieved. During the simulation, the system behavior is stable, as the passivity (8) is ensured by the condition (15).

The force peaks at 50–55 s and 160–170 s in Figs. 2 and 3 are due to the dissipation K_d in (12) and (13). With the longer round-trip delay $\tau_{rt} = 3$ s, the force peaks in Fig. 3 are larger than those in Fig. 2. This is because according to the condition (15) with the same K_p, the dissipation gain K_d of Fig. 3 needs to be three times larger than that of Fig. 2, as τ_{rt} increases from $\tau_{rt} = 1$ s in Fig. 2 to $\tau_{rt} = 3$ s in Fig. 3.

The force peak at 50–55 s in Fig. 3 is as large as the maximum contact force at 100–150 s. Thus, the human operator may not be able to clearly discern the real contact force from the dissipation force. This large force peak also shows that the human could not move the teleoperator agilely in the free motion. In order to mitigate this large dissipation force, we reduce K_d in (12) and (13) by half (i.e., $K_d = 37.5I_{2\times 2}$). Then, according to (15), we also need to reduce K_p by half. Simulation results under these reduced K_d and K_p with $(\tau_1, \tau_2) = (1.2, 1.8)$ s are given in Fig. 4.

With the reduced K_d, the dissipation force peaks in Fig. 4 become smaller than those in Fig. 3. Thus, the human would make a more agile motion of the teleoperator. However, since K_p is also reduced by half, the human would perceive the wall as more compliant and spongy. This is because, following item 4 of *Theorem 1*, to generate similar forces with a lower K_p, the human needs to push the master further for a larger master–slave position error. In Fig. 4, the human's set point is moved from $(x, y) = (52.5, 0)$ cm to $(x, y) = (63, 0)$ cm, so that the position error can become twice larger and a similar contact force as in Figs. 2 and 3 can be generated with the half-reduced K_p. This shows that the condition (15) imposes a tradeoff between force-reflection sharpness and free-motion agility.

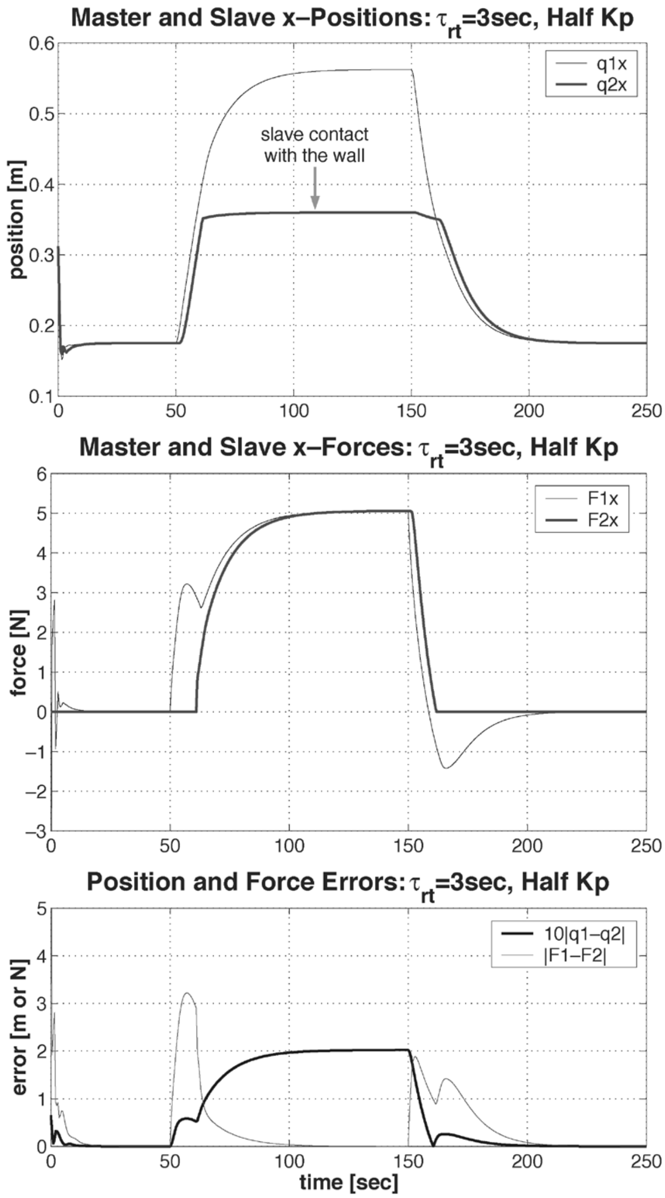

Fig. 4. Simulation result: $\tau_{rt} = 3$ s, $K_p = 25I_{2\times2}$, $K_d = 37.5I_{2\times2}$. To enhance motion agility (i.e., reduce the damping force peaks in Fig. 3), the dissipation gain K_d [also, the P-control gain K_p via (15)] is reduced by half from Fig. 3.

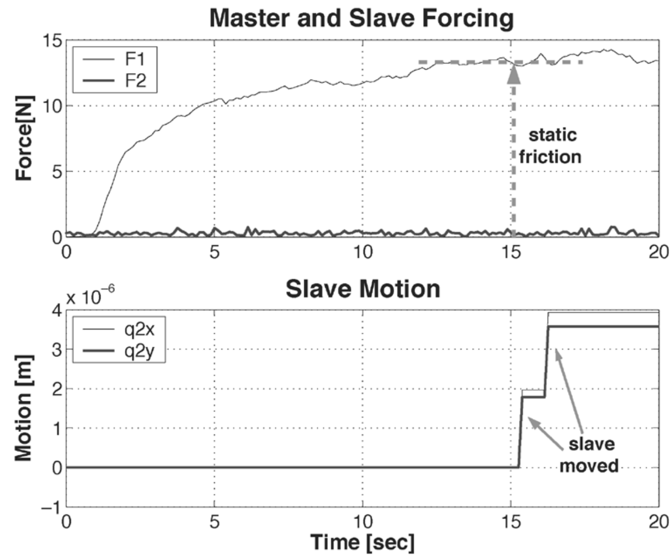

Fig. 5. Coulomb friction in the experiment system.

B. Experiment

For the experiment, we use a pair of identical direct-drive planar 2-serial-links revolute-joint "D2R2" robots [36] as the initial experimental platform. We choose one D2R2 as the master robot, whose distal and proximal links have the lengths of (25,24.5) cm. We also choose the other D2R2 robot as the slave robot and attach an additional link on its distal link, so that its distal and proximal links have lengths of (37.5,24.5) cm. For more details on the physical construction and specification of the D2R2 robot, refer to [36].

The control laws (12) and (13) are derived for the Cartesian-space dynamics (i.e., q_1, q_2 in (1) and (2) as Cartesian x, y positions) so that, following item 4 of *Theorem 1*, the Cartesian (static) force reflection can be achieved. To evaluate the system's contact behavior, we install an aluminum wall in the slave environment. As a real-time operating system, we use Wincon 5.0 (Quanser Inc., ON, Canada) with MatLab SimuLink, and a 2.5 ms sampling rate is obtained. We also measure the human and contact forces [i.e., $F_1(t)$, $F_2(t)$ in (1) and (2)] using force sensors from JR3 Inc. Recall from (12) and (13) that our control laws do not require force sensing.

As reported in [36], in spite of its being of direct-drive robots (i.e., negligible gear friction), the D2R2 robot has substantial bearing friction. This friction was, in part, compensated for in [36] for better trajectory tracking. However, by producing sporadic stictions, such a friction compensation can often disturb and corrupt the human's perception during the teleoperation. Thus, we do not compensate for the friction in this experiment. For the robot's posture frequently encountered during the experiment, we measure the Coulomb friction as shown in Fig. 5, where the human operator increases his force with the slave robot being free to move (i.e., no contact). In Fig. 5, the slave does not move for 15 s. This implies that the (static) Coulomb friction can go up to 12 N.

For the experiment, we choose similar scenario as in Section IV-A: 1) initially, the teleoperator is stabilized with the slave being positioned at a certain start position; 2) then, without seeing, the human operates the master to move the slave close to the aluminum wall and keeps pushing until he perceives the wall; 3) he makes a hard contact; and 4) finally, while seeing the slave environment, the human tries to retract the slave into a certain end position.

Same as in the simulation, we choose the 2-sets of delays: $(\tau_1, \tau_2) =$ (0.4,0.6) s (i.e., $\tau_{rt} = 1$ s) and $(\tau_1, \tau_2) =$ (1.2,1.8) s (i.e., $\tau_{rt} = 3$ s). We choose the P-action gain K_p in (12) and (13) to be the same for these two delay sets, and set the dissipation gain K_d according to the condition (15). Thus, K_d for $(\tau_1, \tau_2) =$ (1.2,1.8) s is three times larger than that for $(\tau_1, \tau_2) =$ (0.4,0.6) s. Additional damping P_ϵ is omitted in the control implementation, as we leave the device friction uncompensated. Experimental results with these two delay sets are given in Figs. 6 and 7, respectively. Similar to the simulation (Fig. 4), in order to enhance motion agility, we reduce K_d [and

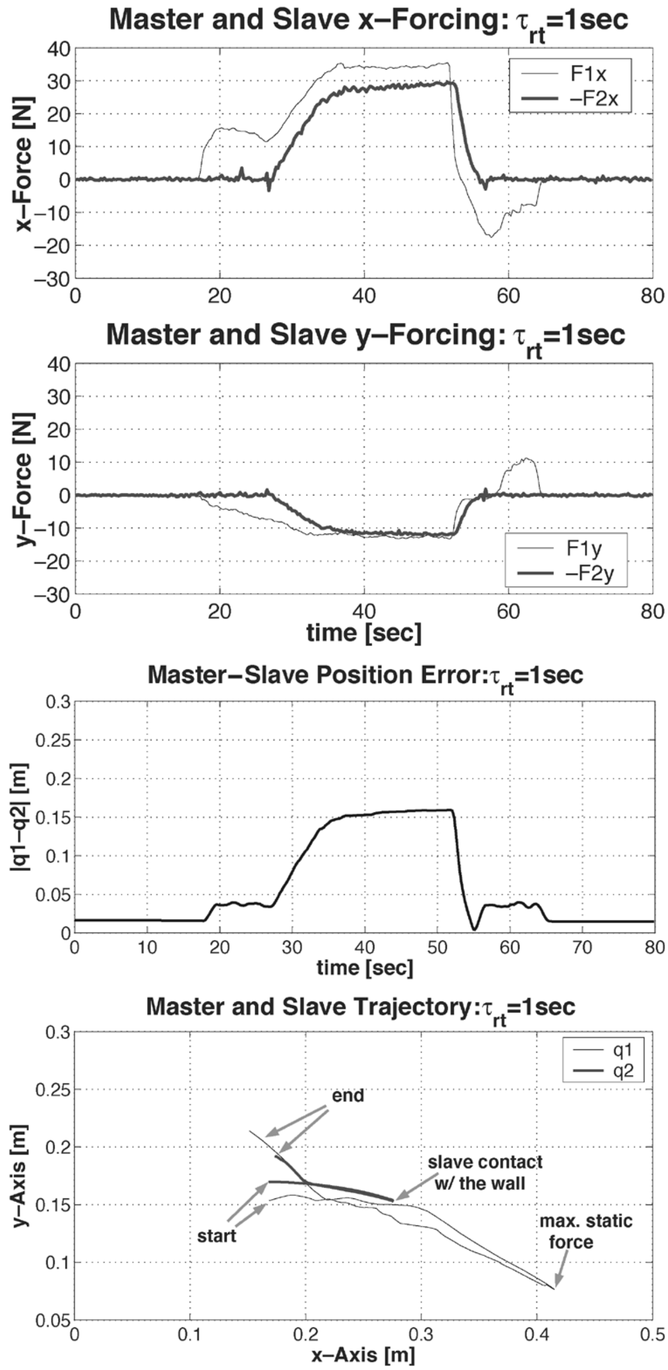

Fig. 6. Experimental result with the round-trip delay $\tau_{rt} = 1$ s.

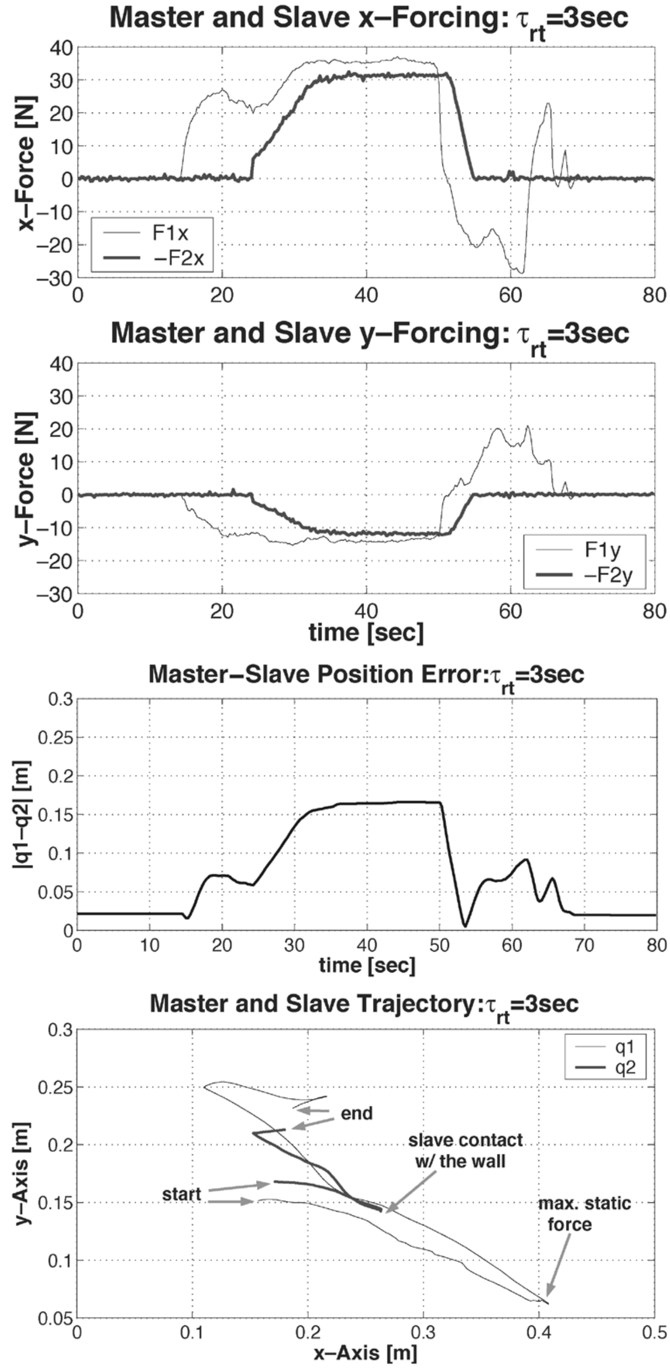

Fig. 7. Experimental result with the round-trip delay $\tau_{rt} = 3$ s.

K_p via (15)] by half for the delay $(\tau_1, \tau_2) =$ (1.2,1.8) s, and present the result in Fig. 8.

As shown by human force profiles in Figs. 6–8, the human operator can perceive the aluminum wall through the force reflection. Also, in the free motion, the master and slave positions become coordinated with each other. These free motion and contact behaviors are all stable, as we enforce passivity (8) through the condition (15). In Figs. 6–8, there are some errors in both the force reflection (e.g., around 40 s) and position coordination (e.g., around 80 s). We think that these errors are mainly due to the substantial device Coulomb friction, as reported in Fig. 5. Also, notice that the master's trajectory becomes more wiggly with longer delays and less K_p. This is consistent with the fact that the human had more difficulty in positioning the slave into a certain desired end position as K_p becomes less and/or the delays become longer.

As shown in Figs. 6 and 7, under the condition (15), free-motion agility is compromised (i.e., larger K_d), when the delays become longer. In Fig. 8, with K_d being reduced by half from Fig. 7, the dissipation force peaks are reduced. However, with the condition (15), this reduction of K_d also requires K_p to be reduced by half, so that to generate a similar contact force, the master–slave position error needs to be twice larger than that in Fig. 7 (i.e., less sharp force reflection).

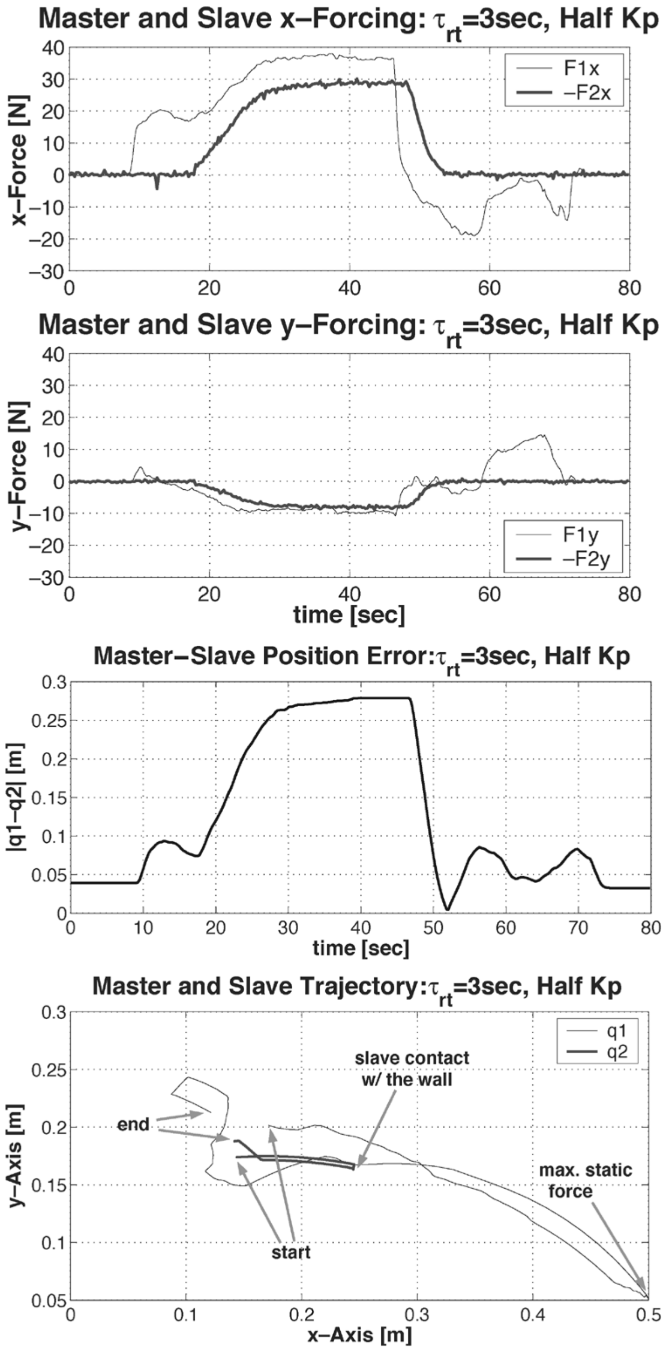

Fig. 8. Experimental results with the round-trip delay $\tau_{rt} = 3$ s. To enhance motion agility (i.e., to reduce damping force peaks in Fig. 7), the dissipation gain K_d [also the P-action gain K_p via (15)] is reduced by half.

When a human operator makes a static contact with a fixed remote object (e.g., the aluminum wall), following item 4 of *Theorem 1*, s/he will perceive the remote object via the serial connection of the P-action spring K_p and the object's compliance (say K_e). Thus, the apparent compliance perceived by a human is dominated by either K_e or K_p, whichever is smaller. For this experiment, since the P-gain is less than the compliance of the aluminum wall, it was difficult for the human to perceive the wall's compliance (or hardness), although he could still feel its position and shape via the deflection of the P-action spring.

During the experiment, we did not observe any nonpassive behaviors possibly associated with the sampling process and sensor quantization. We believe that this is due to the relatively large uncompensated device friction in the experimental setup. For more details on this subject, refer to [37].

The simulation and experimental results in Section IV-A and Section IV-B together highlight the effects of the condition (15) or (14) on the system performance: 1) if we want to keep the same force-reflection performance (i.e., same K_p) with longer communication delays, motion agility needs to be compromised (i.e., larger K_d is required); and 2) when the communication delay is fixed, there is a tradeoff between force-reflection sharpness and free-motion agility, i.e., a small K_d (or large K_p, resp.) allows only a small K_p (or large K_d, resp.).

V. Summary and Conclusions

In this paper, we propose a novel passive bilateral control framework for nonlinear robotic teleoperators with constant communication delays. The proposed framework uses the PD control, which directly connects the master and slave robots via spring and damper over the delayed communication. Without relying on the widely used scattering-based teleoperation, the proposed framework enforces passivity of the closed-loop teleoperator by passifying the combination of the delayed communication and control blocks altogether. To achieve this, the proposed framework uses the controller passivity concept, the Lyapunov–Krasovskii technique, and Parseval's identity. Due to the explicit position feedback provided by the delayed P-action, the proposed framework would prevent position drift between the master and slave robots, which has been well known as the major problem of the conventional scattering-based teleoperation. Under the proposed framework, the closed-loop teleoperator is presented to the human operator as a tool, by which s/he can extend his/her physiological proprioception to the remote slave environments. Simulations and experiments are performed to validate/highlight properties of the proposed control framework.

We believe that the proposed framework is promising for Internet teleoperation, where its explicit position feedback would serve a role in recovering the master–slave position coordination in the presence of packet loss and time-varying delays.

The proposed framework aims to achieve a good EPP, which mainly concerns the low-frequency performance. Therefore, for the cases where a given task requires an operation in a high-frequency region (e.g., detection of a sharp edge, or "asymmetric information feedback" [38]), we will investigate high-frequency characteristics of the proposed framework. When the master and slave are LTI, this can be easily done by computing the transfer-function bandwidth or transparency [17]. However, for the general nonlinear master and slave, we would need a different approach, as the frequency-response concept becomes inapplicable.

We also believe that this proposed framework can be used in conjunction with other schemes to improve the system performance and stability. One possibility is to augment the proposed framework with another control scheme designed for a certain high-frequency region. By doing so, we may be able to enjoy a good performance both in the low-frequency (by the proposed framework) and high-frequency (by the augmented control) regions.

APPENDIX

A. Derivation of $G_1^t(w)$ for (29)

The Fourier transform $G_i^t(w)$ of $g_i^t(\theta)$ in (28) is defined by

$$G_i^t(w) := \int_{-\infty}^{+\infty} g_i^t(\theta) e^{-jw\theta} d\theta = \underbrace{\int_{-\infty}^{+\infty} \left[\int_{-\infty}^{\theta} \tilde{\dot{q}}_i^t(\xi) d\xi\right] e^{-jw\theta} d\theta}_{=:P_1^i(w)} - \underbrace{\int_{-\infty}^{+\infty} \left[\int_{-\infty}^{\theta-\tau_i} \tilde{\dot{q}}_i^t(\xi) d\xi\right] e^{-jw\theta} d\theta}_{=:P_2^i(w)}. \quad (40)$$

Let us define the step-function $1_\tau(\theta)$ with a time offset $\tau \in \Re$ s.t. $1_\tau(\theta) = 1$ if $\theta - \tau \geq 0$, and $1_\tau(\theta) = 0$, otherwise. Then, following [39, pp. 38], its Fourier transform can be computed by

$$\int_{-\infty}^{+\infty} 1_\tau(\theta) e^{-jw\theta} d\theta = \int_{-\infty}^{+\infty} \left[\frac{1}{2} + \frac{1}{2}\mathrm{sgn}(\theta - \tau)\right] e^{-jw\theta} d\theta = \pi\delta(w) + \frac{e^{-jw\tau}}{jw} \quad (41)$$

where $\delta(w)$ is the delta impulse function w.r.t. w, whose magnitude represents the dc component of the signal $1_\tau(\theta)$ (i.e., 1/2), and $\mathrm{sgn}(\theta)$ is the signum function s.t. $\mathrm{sgn}(\theta) = 1$ if $\theta \geq 0$, and $\mathrm{sgn}(\theta) = -1$, otherwise. The key facts for achieving (41) are $(1/2\pi)\int_{-\infty}^{+\infty} 2\pi\delta(w) e^{jw\theta} dw = 1$ (i.e., Fourier transform of 1 is $2\pi\delta(w)$), and

$$\frac{1}{2\pi}\int_{-\infty}^{+\infty} \frac{2}{jw} e^{jw(\theta-\tau)} dw = \frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{\sin w(\theta - \tau)}{w} dw = \mathrm{sgn}(\theta - \tau)$$

(i.e., the Fourier transform of $\mathrm{sgn}(t - \tau)$ is $(2/jw)e^{-jw\tau}$).

Now, as in [39, pp. 40], we can rewrite $P_2^i(w)$ in (40) s.t.

$$P_2^i(w) = \int_{-\infty}^{+\infty} \left[\tilde{\dot{q}}_i^t(\theta) * 1_{\tau_i}(\theta)\right] e^{-jw\theta} d\theta \quad (42)$$

where $*$ is the convolution operator. Thus, using (41), we have

$$P_2^i(w) = V_i^t(w)\left[\pi\delta(w) + \frac{e^{-jw\tau_i}}{jw}\right]. \quad (43)$$

Similarly, by setting $\tau_i = 0$ in (42) and using (41), $P_1^i(w)$ in (40) can be written as

$$P_1^i(w) = V_i^t(w)\left[\pi\delta(w) + \frac{1}{jw}\right]. \quad (44)$$

Thus, combining (44) and (43), $G_i^t(w)$ in (40) is given by

$$G_i^t(w) = V_i^t(w)\frac{1 - e^{-jw\tau_i}}{jw}, \quad i = 1, 2. \quad (45)$$

Here, note that $G_i^t(w)$ does not have any dc component (i.e., no impulse at $w = 0$), since the dc component of the delayed signals [i.e., $\pi\delta(w)$ in (44)] is the same as that of the original signal [i.e., $\pi\delta(w)$ in (43)] and are cancelled out by each other to make $G_i^t(w)$ in (45).

B. Derivations for the Last Line of (29)

Let us define $I_i(t)$ s.t., for $(i, k) = \{(1, 2), (2, 1)\}$

$$I_i(t) := \int_{-\infty}^{+\infty} V_i^{t*}(w) K_p \frac{1 - e^{-jw\tau_k}}{jw} V_k^t(w) dw. \quad (46)$$

Then, using a dummy integration variable $w' = -w$, $I_i(t)$ can be rewritten as

$$I_i(t) = \int_{-\infty}^{+\infty} V_i^{t*}(-w') K_p \frac{1 - e^{jw'\tau_k}}{-jw'} V_k^t(-w') dw' = \int_{-\infty}^{+\infty} V_k^{t*}(w') K_p \frac{1 - e^{jw'\tau_k}}{-jw'} V_i^t(w') dw' \quad (47)$$

where we use the fact that $V_i^{t*}(-w') K_p V_k^t(-w') = V_k^{t*}(w') K_p V_i^t(w')$, because K_p is symmetric and $V_i^t(-w') = \bar{V}_i^t(w')$ from the definition of the Fourier transform. Thus, by rewriting $I_i(t)$ in (29) as the average of (46) and (47), with the dummy variable w' replaced by w, the last line of (29) can be achieved.

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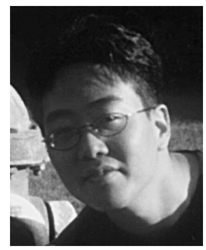

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