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Position Synchronization in Bilateral Teleoperation Under Time-Varying Communication Delays

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***Abstract*—Passivity-based approaches to bilateral teleoperation sacrifice performance to achieve robust stability against time-varying delays. Typically, force and velocity signals are exchanged in passivity-based bilateral teleoperation resulting in good velocity tracking, but may accrue a position drift. Recently, a *power-based* time domain passivity approach (TDPA) was proposed to passivate the communication channel in bilateral teleoperation with time-varying delays, which has the potential to be less conservative than other time-invariant passivity-based approaches. Several approaches have been proposed to address the problem of position drift in time-invariant passivity-based approaches to bilateral teleoperation, but the problem of position drift with power-based TDPA remains unsolved. We propose a feedback passivity-control-based scheme to achieve position synchronization in bilateral teleoperation with power-based TDPA. Our proposed method encodes position information with velocity to construct a composite signal, which is transmitted across the communication channel to attain position tracking. The proposed method utilizes time delay power network formulation, enabling extension to position-measured force bilateral teleoperation scheme. Simulations and experiments conducted on a custom one degree of freedom teleoperation setup demonstrate robust position tracking performance with our approach under time-varying communication delays and remote environment conditions.**

***Index Terms*—Adaptive control, delay systems, robust stability, telerobotics, time-varying systems.**

I. Introduction

BILATERAL teleoperation is defined as a human operator using a robotic system to manipulate objects at a distance, while receiving haptic feedback of remote environment interaction forces [1]. Typically, a bilateral teleoperation system consists of a master robot for expressing operator's intention and providing force feedback, a communication channel transmitting command, and feedback signals between local and remote locations, and a slave robot which follows operator's commands and interacts with the remote environment. Energetically, this system can be viewed as an interconnection of various subsystems as shown in Fig. 1, exchanging energy through transmission of force and velocity signals. The idea of passivity characterized by mechanical energy (i.e., using force and velocity as effort and flow variables) has long been a convenient tool for establishing stability of bilateral teleoperation interaction [2], [3].

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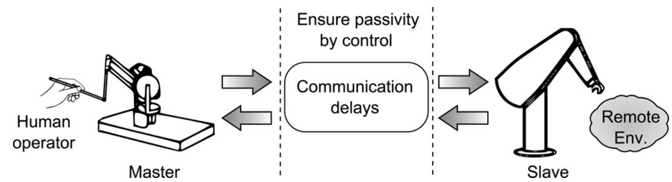

Fig. 1. Communication delays are the main source of activity in bilateral teleoperation. Passivity-based approaches aim to use control for passivating the communication channel, and hence ensure system passivity.

Interconnection of passive systems is always passive [4], which allows analyzing passivity of an interconnected system by considering the passivity of each constituent system separately. Methods based on absolute stability promise less conservative performance than conventional passivity-based approaches [5], but are typically more complex, cannot easily accommodate variable communication time delays, and require information about remote environment and operator impedance characteristics [6], [7]. In this paper, we will limit our discussion to passivity-based approaches.

The master and slave devices (in absence of any local force feedback) are always passive. However, time delays introduced by the communication channel are a source of activity and may cause instabilities [2], [8]. Passivity-based approaches such as wave variables [8] and scattering approach [2] were proposed to ensure passivity of the communication channel with constant time delays. Several methods building on these two approaches have been proposed for ensuring passive teleoperation under time delays (see [9], [10], and [11] for a detailed survey). While these methods can guarantee passive teleoperation, due to their "time-invariant" nature, they overdissipate energy by considering the worst-case scenario. This overdissipation of energy by the time-invariant methods ensures robust stability against time delays at the cost of having conservative performance. Recently, an energy-based Time Domain Passivity Approach (TDPA) was proposed by Hannaford *et al.* [12] to circumvent the issue of overdissipation and adaptively dissipate energy as needed. The TDPA consists of two main components: a *passivity observer* (PO) which monitors the system passivity in real time, and a *passivity controller* (PC) which dissipates the active energy generated by the system as computed by the PO. The TDPA was extended to the case of time-varying communication delays in [13], and promises less conservatism than time-invariant passivity-based approaches due to time-dependent energy dissipation by the PC. The energy-based TDPA, while less conservative than the time-invariant passivity-based approaches, suffers from sudden force changes felt at the master due to highly nonlinear corrections introduced by the PC for enforcing passivity. Energy is computed by integrating the power flow, which may allow for some active behavior before being detected by the PO. Also, transmission of energies between master and slave, and carefully keeping track of energy states of communication channel ports complicates the PO computation.

A power-based TDPA was proposed by Ye *et al.* in [14] to alleviate some of the issues with energy-based TDPA by constructing a simplified PO/PC architecture which dissipates energy as soon as any active power is generated. This eliminates the need for integrating power to compute energy and does not require exchanging energies over the communication channel. Another benefit is smoother force reflection at the master side because the PC action is distributed over a longer period of time. However, transparency in power-based TDPA is degraded due to a more conservative enforcement of passivity based on power. Furthermore, like energy-based TDPA, a significant position drift is accrued due to modification of the transmitted master velocity by the slave PC to ensure passivity. Also, the power-based TDPA in [14] was limited to position-computed force bilateral architecture where slave controller force is reflected to the master as a proxy for remote environment interaction forces. Using slave control force as feedback presents human operator with the slave device and controller dynamics, which is further detrimental to the transparency of bilateral teleoperation. With severely distorted force reflection and poor correspondence between master and slave device positions, the power-based TDPA approach is very limited for practical applications.

The approach in this paper differs from earlier power-based TDPA on several important points.

1) We resolve the problem of position drift in power-based TDPA by applying the concept of feedback passivity[15] in the time domain to encode position information with velocity. We then transmit the encoded information over the communication channel for synchronizing the positions of master and slave devices.
2) We apply the recently proposed time delay power network (TDPN) formulation [16] to generalize power-based TDPA to position-measured force architecture, where force measured at the environment is reflected back to the master, thus masking the slave controller and slave device dynamics. The earlier approach was limited to position-computed force teleoperation scheme.

Passivity of bilateral teleoperation with our proposed approach is analyzed theoretically. Simulation and experimental results with a one-degree-of-freedom (DOF) bilateral teleoperation setup under time-varying delays and different force feedback schemes (computed force and measured force) are presented to demonstrate the efficacy of our approach. Our approach is suitable for bilateral teleoperation systems with time-varying delays requiring good position tracking, smooth force reflection, simple computation, and ability to use measured remote interaction forces as feedback to the master.

II. Passivating Communication Channel With Power-Based TDPA

In this section, we will review the TDPN representation of the communication channel, and perform passivity analysis of

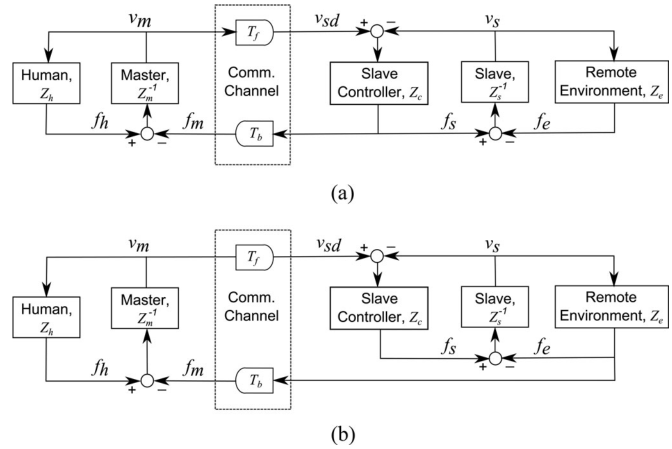

Fig. 2. Block diagrams representations of the position-force teleoperation schemes considered in this paper. (a) P-CF scheme. (b) P-MF scheme.

the TDPN with power-based TDPA. PO and PC formulations for both impedance- and admittance-type causality will be described, and the origin of position drift between master and slave devices will be explored.

A. TDPN Formulation

TDPN is defined as a two-port network that characterizes the delay in transmission of signals from one port to another, completely described by the pairs of power-conjugated variables at each port [16]. This formulation is particularly useful in modeling the communication channel when network causality is ambiguous, such as the case with position-measured force (P-MF) or position–position teleoperation schemes. The basic idea behind TDPN formulation is to identify the root of command and feedback signals, and represent them with corresponding ideal flow and effort sources.

In this paper, we consider two types of position-force teleoperation schemes. The first is called the position-computed force (P-CF) scheme, where the slave device follows the position commands from the master device, and delayed slave control force is sent back to the master as the feedback force, as shown in Fig. 2(a). The second is called the P-MF scheme, where the force sensed during remote environment interaction is reflected back to the master as the feedback force, as shown in Fig. 2(b). The master and slave device velocities are denoted by v_m and v_s; v_{sd} is the desired velocity command signal to the slave controller; f_m and f_s are the master and slave control forces; f_h is the force applied by operator; and f_e is the remote environment interaction force. The time-varying forward and backward communication delays are denoted by T_f and T_b.

Using the TDPN formulation, the P-CF and P-MF teleoperation schemes can be represented in electrical network representation as shown in Fig. 3.

B. Passivity Analysis of TDPN

A power-based TDPA was proposed in [14] to passivate the communication channel in bilateral teleoperation under the P-CF scheme. Here, we extend the ideas proposed in [14] in order

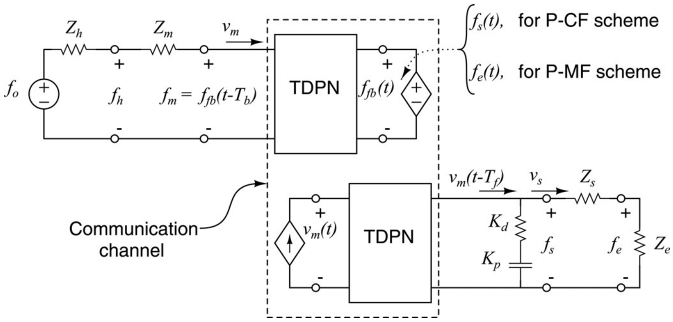

Fig. 3. Electrical network representation of P-F teleoperation schemes using TDPN formulation.

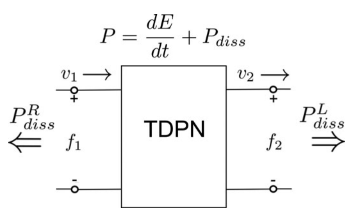

Fig. 4. Power flow in a TDPN. The power dissipated by the TDPN is divided into components observable at its left and right ports.

to passivate the communication channel in bilateral teleoperation under both P-CF and P-MF schemes. This is accomplished by formulating POs which monitor the passivity of TDPNs comprised in the communication channel, and PCs which dissipate any active energy generated by the TDPNs.

Fig. 4 shows the power flow into the TDPN. The power flow is given as

$$P = f_1(t)v_1(t) - f_2(t)v_2(t) \tag{1}$$

where $f_1(t), v_1(t)$ are the power correlated effort and flow signals at the left port and $f_2(t), v_2(t)$ are the power correlated signals at the right port. Signs of forces and velocities have been chosen such that $f_1(t)v_1(t)$ represents power flow *into* the TDPN and $f_2(t)v_2(t)$ represents power flow *out of* the TDPN. For the sake of brevity, we will drop the time dependence of the signals as appropriate. Introducing a positive constant b relating the units of force and velocity [8], and following the approach described in [14], we can write the power flow as

$$\begin{aligned} P = \frac{1}{2b}f_1^2 + \frac{b}{2}v_1^2 - \frac{1}{2b}(f_1 - bv_1)^2 \\ + \frac{1}{2b}f_2^2 + \frac{b}{2}v_2^2 - \frac{1}{2b}(f_2 + bv_2)^2. \end{aligned} \tag{2}$$

Using the signal transmission relations

$$\begin{aligned} v_2(t) &= v_1(t - T_f(t)) \\ f_1(t) &= f_2(t - T_b(t)) \end{aligned} \tag{3}$$

where $T_f(t)$ and $T_b(t)$ are the time-varying forward and backward communication delays, we can write the power flow as

$$\begin{aligned} P &= \frac{1}{b}f_1^2 - \frac{1}{2b}(f_1 - bv_1)^2 + bv_2^2 - \frac{1}{2b}(f_2 + bv_2)^2 \\ &\quad - \frac{b}{2}\dot{T}_f v_2^2 - \frac{1}{2b}\dot{T}_b f_1^2 + \frac{d}{dt}\int_{t-T_b}^{t} \frac{1}{2b}f_2^2(\tau)d\tau \\ &\quad + \frac{d}{dt}\int_{t-T_f}^{t} \frac{b}{2}v_1^2(\tau)d\tau \\ &= \frac{dE}{dt} + P_{\text{diss}} \end{aligned} \tag{4}$$

where

$$E(t) = \int_{t-T_b}^{t} \frac{1}{2b}f_2^2(\tau)d\tau + \int_{t-T_f}^{t} \frac{b}{2}v_1^2(\tau)d\tau, \text{ and} \tag{5}$$

$$\begin{aligned} P_{\text{diss}}(t) &= \frac{1}{b}f_1^2 - \frac{1}{2b}(f_1 - bv_1)^2 + bv_2^2 - \frac{1}{2b}(f_2 + bv_2)^2 \\ &\quad - \frac{b}{2}\dot{T}_f v_2^2 - \frac{1}{2b}\dot{T}_b f_1^2 \ . \end{aligned} \tag{6}$$

It can be observed from (5) that

$$E(t) \geq 0. \tag{7}$$

For passivity of the TDPN, the net energy flow in the TDPN must be positive [17]. Using this definition of passivity, and (4) and (7), we get

$$\begin{aligned} E_{\text{flow}}(t) &= \int_0^t P(\tau)d\tau \geq 0 \\ &= \int_0^t \left(\frac{dE}{dt} + P_{\text{diss}}\right)(\tau)d\tau \\ &= E(t) - E(0) + \int_0^t P_{\text{diss}}(\tau)d\tau \\ &\geq -E(0) + \int_0^t P_{\text{diss}}(\tau)d\tau \end{aligned}$$

assuming $E(0) = 0$,

$$\geq \int_0^t P_{\text{diss}}(\tau)d\tau. \tag{8}$$

Thus, if the condition $P_{\text{diss}} \geq 0$ is true, then from (8) we get $E_{\text{flow}} \geq 0$, and the TDPN is passive.

C. Passivity Observer

$P_{\text{diss}}(t)$ is not observable in real time at any single port of the TDPN, thus to facilitate real-time monitoring of TDPN passivity, we can write

$$P_{\text{diss}}(t) = P^L_{\text{diss}}(t) + P^R_{\text{diss}}(t) \tag{9}$$

where $P^L_{\text{diss}}(t)$ and $P^R_{\text{diss}}(t)$ are the power dissipation components which are observable at the left and right ports, respectively, and are given as

$$\begin{aligned} P^L_{\text{diss}}(t) &= \frac{1}{b}f_1^2 - \frac{1}{2b}(f_1 - bv_1)^2 - \frac{1}{2b}\dot{T}_b f_1^2 \\ P^R_{\text{diss}}(t) &= bv_2^2 - \frac{1}{2b}(f_2 + bv_2)^2 - \frac{b}{2}\dot{T}_f v_2^2. \end{aligned} \tag{10}$$

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It can be seen that both $P^L_{\text{diss}}(t)$ and $P^R_{\text{diss}}(t)$ are only composed of signals that are observable at left and right ports, respectively.

The PO computes in real time the power dissipation components given by (10). Since $\dot{T}_f$ and $\dot{T}_b$ are not measurable in real time, a more conservative estimate of $P^L_{\text{diss}}(t)$ and $P^R_{\text{diss}}(t)$ can be made by assuming a constant maximum bound ϵ on $\dot{T}_f$ and $\dot{T}_b$. The PO is given as

$$P^L_{\text{obs}}(t) = \frac{1}{b}f_1^2 - \frac{1}{2b}(f_1 - bv_1)^2 - \frac{1}{2b}\epsilon f_1^2$$
$$P^R_{\text{obs}}(t) = bv_2^2 - \frac{1}{2b}(f_2 + bv_2)^2 - \frac{b}{2}\epsilon v_2^2. \quad (11)$$

It can be assumed for bilateral teleoperation systems that $\epsilon \leq 1$, so if no other information is available about the nature of communication delays, $\epsilon = 1$ can be taken as a conservative estimate [18].

D. Passivity Controller

The passivity condition for TDPN was derived in Section II-B. as $P_{\text{diss}} \geq 0$. The PC modifies the force or velocity signals depending on the causality of the port to enforce this passivity condition.

In an impedance configuration [see Fig. 5(a)], the PC is given as

$$f_m(t) = \hat{f}_m(t) + \alpha(t)v_m(t) \quad (12)$$

where $\hat{f}_m(t)$ is the force signal coming out of the TDPN port and $f_m(t)$ is the force signal after modification by PC. The coefficient $\alpha(t)$ is given as

$$\alpha(t) = \begin{cases} 0, & \text{if } P^L_{obs}(t) > 0 \\ -\frac{P^L_{\text{obs}}(t)}{v_m^2(t)} & \text{else, if } |v_m(t)| > 0. \end{cases} \quad (13)$$

In an admittance configuration [see Fig. 5(b)], the PC is given as

$$v_{sd}(t) = \hat{v}_{sd}(t) + \beta(t)f_s(t) \quad (14)$$

where $\hat{v}_{sd}(t)$ is the velocity signal coming out of the TDPN port, and $v_{sd}(t)$ is the velocity signal after modification by the PC. The coefficient $\beta(t)$ is given as

$$\beta(t) = \begin{cases} 0, & \text{if } P^R_{\text{obs}}(t) > 0 \\ \frac{P^R_{\text{obs}}(t)}{f_s^2(t)} & \text{else, if } |f_s(t)| \quad > 0. \end{cases} \quad (15)$$

The PCs described by (12) and (14) ensure that the TDPN remains passive (see Appendix A for proof). It should be noted that when the transmitted signals (v_m or f_s) are zero, the respective coefficients α and β computed using those signals are set to zero.

Passivity of ideal flow and effort sources: We described the use of PO/PC pairs at each port of a generic TDPN to enforce passivity. In the special case when one port of the TDPN is connected to an ideal flow or effort source, passivity needs to be enforced only at the opposite port [16]. This is because ideal sources can absorb an infinite amount of energy. A change in flow or effort signal about a complementary ideal source will have no effect on the value of that ideal source. Thus, any active energy generated by the TDPN and flowing toward the ideal source will not affect the passivity of the system, and therefore a PO/PC pair is not needed to enforce passivity at that port.

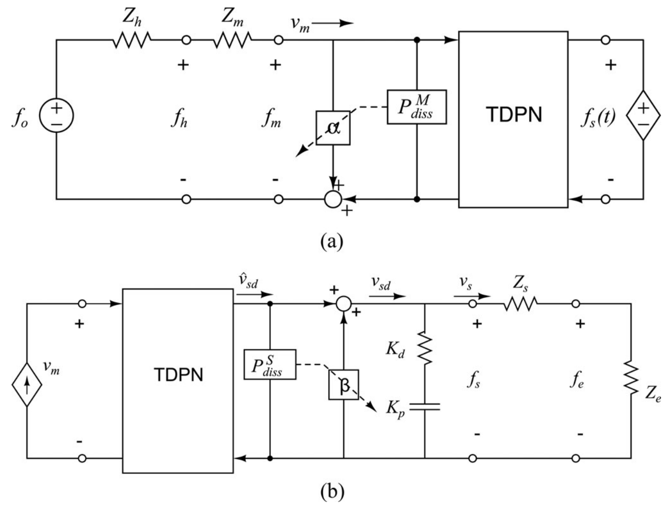

Fig. 5. Passivated TDPN with the PO/PC. Note that the PC is not required on the ports connected to the ideal sources. (a) PO/PC in impedance configuration. (b) PO/PC in admittance configuration.

E. Cause of Position Drift

In position-force teleoperation schemes, the slave controller ideally should be a *proportional-derivative* (PD) controller acting on the error between the position command from the master and slave device's current position. However, since position and force are not power correlated, the velocity signal is transmitted over the communication channel as shown in Fig. 5(b). The position command from the master (x_{sd}) is obtained by integrating transmitted velocity as

$$x_{sd}(t) = \int_0^t v_{sd}(\tau)d\tau. \quad (16)$$

The slave PC has admittance causality and modifies the delayed master velocity $\hat{v}_{sd}(t)$ to dissipate power as given by (14). Thus, the modified position command signal for the slave controller incurs drift given as

$$x_{\text{err}}(n) = \int_0^t v_{sd}(\tau)d\tau - \int_0^t \hat{v}_{sd}(\tau)d\tau$$
$$= \int_0^t \beta(\tau)f_s(\tau)d\tau. \quad (17)$$

Due to the integral action, whenever the slave PC is active ($\beta(t) \neq 0$ and $f_s(t) \neq 0$), a drift in commanded position to the slave controller is accumulated. This drift remains in place even after the PC stops modifying the velocity signal. The root cause of the drift is the absence of absolute position information from the master device. Transmission of position instead of velocity would provide slave controller with accurate position commands from the master, but this is not possible since position and force are not power correlated.

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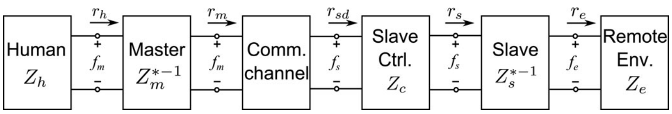

Fig. 6. Two-port network representation of a bilateral teleoperation system. The flow variable is $r(t) = \dot{x}(t) + \lambda x(t)$.

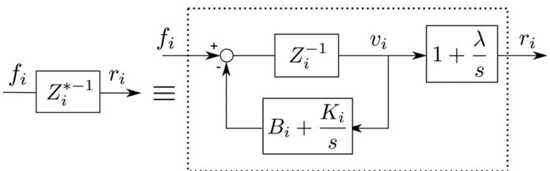

Fig. 7. Block diagram showing the devices augmented with a local FPC to passivate them with respect to $r(t) = \dot{x}(t) + \lambda x(t)$.

III. Position Synchronization in Power-Based TDPA Using r-Passivity

We propose to alleviate the problem of position drift by defining a new signal $r(t) = \dot{x}(t) + \lambda x(t)$ which comprises both position and velocity information, and transmitting this signal over the communication channel instead of velocity alone. This augmented signal "r" has been previously used to counter position drift in wave-variable-based time-invariant approaches to bilateral teleoperation [19] [20]. Here, λ is a positive constant. With this formulation, position information is encoded with the velocity signal, and the slave controller can recover position tracking in the moments when the slave PC is not active. Hereafter, we will refer to passivity with respect to the signal $r(t)$ as "*r-passivity*."

A. r-Passivity Analysis of the Bilateral Teleoperation System

The block diagram representations of the P-CF and P-MF bilateral teleoperation schemes can be represented as a two-port network exchanging force and "r" signals as shown in Fig. 6. If each subsystem forming the two-port network is r-passive, then the whole teleoperation systems will be rendered r-passive. In the following sections, we will analyze r-passivity of each subsystem, and describe how the position drift is compensated.

1) r-Passivity of the Master and Slave Devices: The master and slave devices are passive with respect to the velocity signal and not $r(t)$. Following the approach proposed in [20], a local *Feedback Passivity Controller* (FPC) is employed to modify the dynamics of the devices and render them passive with respect to $r(t)$, as shown in Fig. 7.

The master (Z_m) and slave (Z_s) devices are modeled as

$$m_i \ddot{x}_i + b_i \dot{x}_i = f_i^{\text{con}} + f_i^{\text{ext}}, i = m, s \quad (18)$$

where f_i^{ext} is the external force applied to the devices by the human operator (f_h) or the remote environment (f_e), and f_i^{con} is the controller force. f_i^{con} is given as

$$f_i^{\text{con}} = f_i^{\text{FPC}} + f_i, i = m, s \quad (19)$$

where f_i is the control force from the master ($i = m$) or slave ($i = s$) controllers, and f_i^{FPC} is the contribution from the local FPC, given as

$$f_i^{\text{FPC}} = -B_i \dot{x}_i - K_i x_i. \quad (20)$$

B_i and K_i are the parameters of the FPC, which must be chosen such that the following conditions are satisfied:

$$b_i + B_i > \lambda m_i \ , \ \lambda > 0 \ \text{ and } K_i > 0 \quad (21)$$

to ensure r-passivity of the devices. See Appendix B for proof of (21).

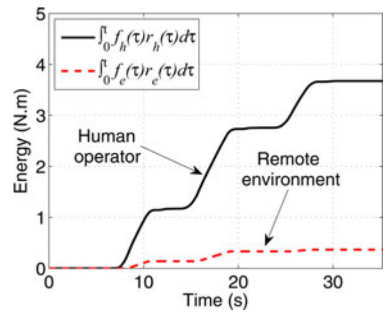

Fig. 8. Representative plot showing passivity of human operator and remote environment with respect to $r_i(t) = \dot{x}_i(t) + \lambda x_i(t)$. The operator force ($f_h$) and environment force (f_e) were measured to compute energy values.

2) r-Passivity of the Communication Channel: The communication channel is composed of two TDPNs as shown in Fig. 3. The communication channel is rendered passive if both TDPNs comprised in the communication are made passive with PO/PC pairs. The power flow through the TDPN given by (1) is now replaced by

$$P = f_1(t) r_1(t) - f_2(t) r_2(t) \quad (22)$$

and the reminder of the analysis is carried out as detailed in Sections II-B–II-D. by replacing v_i with r_i. For ensuring r-passivity of the communication channel, the PO/PC formulation is changed to treat $f_i(t)$-$r_i(t)$ as the power-correlated signals instead of the $f_i(t)$-$v_i(t)$ pair.

Remarks on r-Passivity of the human operator, remote environment, and slave controller: We have assumed that the environment and the human operator are passive with respect to $r_i(t)$. If the environment is modeled as a spring-damper system, then the r-passivity assumption can be readily verified. Although the human operator is generally assumed to be passive with respect to the velocity signal, it is still reasonable to assume passivity with respect to $r(t)$ since the operator generally keeps the velocity and position of the teleoperator bounded and tries to bring them back to the initial state eventually [20]. Similar assumptions regarding r-passivity of the operator/environment can also be found in [19], [21], and [22]. In our experiments, we observed this assumption to hold true, as shown in Fig. 8.

The slave controller is a *proportional* controller acting on "r-error" given by (23), which can easily shown to be r-passive. With r-passivity of all the subsystems forming the bilateral teleoperation system (see Fig. 6) established, we can claim that the whole system is r-passive.

TABLE I
MASTER AND SLAVE DEVICE PARAMETERS

Parameters	Master	Slave
m (kg)	0.52	0.31
b (Ns/m)	13.2	4.06
f_c (N)	0.19	0.16

B. Compensation of Position Drift

With $r(t)$ as the transmitted signal instead of velocity, the slave controller which was earlier a *PD*-controller acting on position error between delayed master position and current slave position is replaced by an equivalent *proportional* controller acting on "r-error," given as

$$\begin{aligned} f_s(t) &= K_{pr}(r_{sd}(t) - r_s(t)) \\ &= K_{pr}(v_{sd}(t) - v_s(t)) + K_{pr}\lambda(x_{sd}(t) - x_s(t)) \end{aligned} \tag{23}$$

which is similar to the position error *PD*-controller with proportional and derivative gains as $K_{pr}\lambda$ and K_{pr}, respectively. The important difference now is that the commanded position $x_{sd}(t)$ is not computed by integrating $v_{sd}(t)$. Thus, any corrections done by the PC to the $r_{sd}(t)$ signal for enforcing system passivity are not accumulated. As soon as the slave PC is inactive, accurate unmodified command position will be available to the slave controller, thus eliminating position drift resulting from drift in commanded position.

IV. SIMULATION AND EXPERIMENTAL RESULTS

A. Simulations

The proposed scheme was implemented in simulation using Simulink. Master and slave devices are modeled as one-DOF linear mass–damper systems with Coulomb friction (f_c) to simulate the dynamics of the experimental setup described later in Section IV-B. The device parameters identified by performing system identification are shown in Table I.

The human operator is modeled as $f_h = b_h \dot{x}_h + k_h x_h$, with parameters $k_h = 700\text{N/m}$ and $b_h = 5\text{N.s/m}$ [23]. The operator attempts to follow a sinusoidal reference trajectory and finally comes to rest at zero position. The forward and backward communication delays, T_f and T_b, were selected to be linearly varying between 50–150ms, increasing over a period of 1 s and then linearly decreasing. The average round-trip delay was 200 ms.

The environment was modeled as a spring with stiffness $k_e = 30$ kN/m. The sampling rate was set at 1000 Hz, and the *ode4*-Runge Kutta solver was used. The devices were simulated as continuous-time models with position output. The output position was quantized with 1 μm resolution to simulate output from a position encoder. The slave PD controller gains were chosen as $K_p = 63.83$ N/m and $K_d = 31.91$ Ns/m. For r-passivity-based TDPA, $\lambda = 2\ s^{-1}$ and $K_{pr} = 31.91$ Ns/m were chosen, to match the PD controller gains chosen for the regular

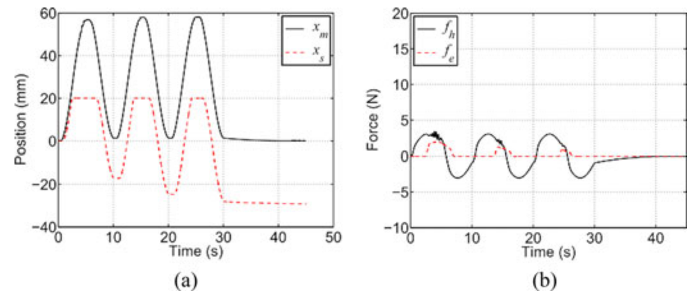

Fig. 9. Simulation results with the P-CF teleoperation scheme employing regular power-based TDPA. (a) Master and slave positions. (b) Operator and environment forces.

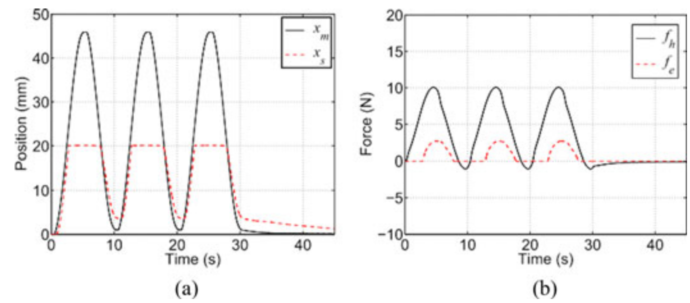

Fig. 10. Simulation results with the P-CF teleoperation scheme employing power-based TDPA with r-passivity. (a) Master and slave positions. (b) Operator and environment forces.

power-based TDPA case. The maximum bound on rate of change of communication delays was taken as $\epsilon = 0.1$. The controller parameters are chosen such that the r-passivity conditions (21) are satisfied.

Figs. 9 and 10 show the simulation results for P-CF teleoperation employing regular power-based TDPA and power-based TDPA with r-passivity, respectively. It should be noted that teleoperation without TDPA was unstable, and the corresponding plots are omitted here due to space constraints.

Simulations were performed for P-MF teleoperation employing power-based TDPA with r-passivity. The plots are similar to the P-CF teleoperation scheme shown in Fig. 10, but the operator is applying slightly less force during free space motion. The primary difference between P-CF and P-MF is visible during free space motion, where the P-MF scheme sends null force feedback, while the P-CF scheme will still feedback some nonzero force to the master due to slave controller and device dynamics. This results in a sluggish free space motion feeling. The P-MF scheme masks the dynamics of the slave controller and the slave device by directly sending back the sensed force to the operator. However, this advantage becomes small when power-based TDPA schemes are used, owing to the significant viscous effect felt due to power dissipation by the PC.

B. Experiments

A teleoperation setup composed of two custom built single DOF linear-impedance-type devices as shown in Fig. 11 was used for the experiments. The slave device was equipped with

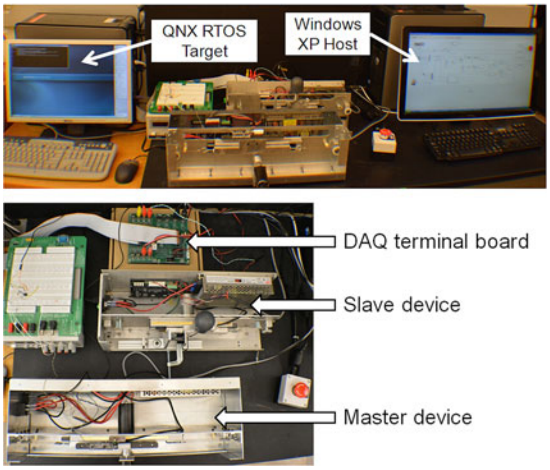

Fig. 11. Teleoperation experimental setup. Master and slave are linear, one DOF devices.

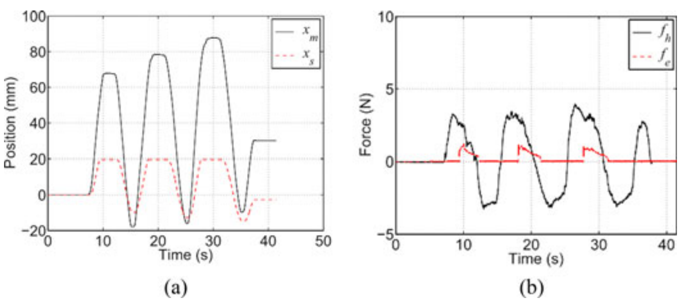

Fig. 12. Experimental results with P-MF teleoperation scheme employing regular power-based TDPA. (a) Master and slave positions. (b) Operator and environment forces.

a single axis force sensor (FC 22, Measurement Specialties) to sense remote environment forces. An aluminum wall was used as the environment. The master device was equipped with a two-axis load cell (ELFS-T3E-5L, Entran) to sense forces applied by the human operator. The sensed force signals were amplified and conditioned, limiting their bandwidth to 40 Hz. Control was implemented using Simulnk+QuaRC on a Windows host and QNX RTOS target computer setup. Both devices were controlled using the same computer, and the communication delay was implemented in software. The control loop rate was set at 1000 Hz. The controller parameters and communication delays were the same as those of the simulation.

Figs. 12 and 13 show the experimental results with P-MF teleoperation scheme. The operator was trying to make contact with the hard wall and apply consistent force repeatedly.

V. Discussion and Conclusion

The simulation and experimental results with power-based TDPA, both with and without r-passivity scheme, demonstrate stable teleoperation under time-varying communication delays. Both the P-CF and P-MF teleoperation schemes demonstrated unstable remote environment interaction without passivity-based control. This is due to active energy introduced by the

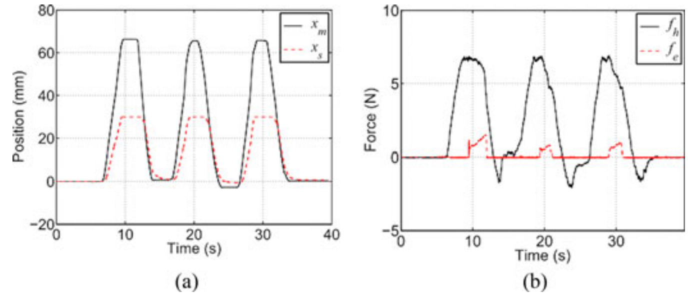

Fig. 13. Experimental results with P-MF teleoperation scheme employing power-based TDPA with r-passivity. (a) Master and slave positions. (b) Operator and environment forces.

delays in the communication channel, which made the entire teleoperation system nonpassive. The time-varying nature of the delays is a further source of activity in the communication channel.

It can be observed from the simulation plots shown in Figs. 9(a) that, with power-based TDPA, although the remote environment interaction is stable, significant position drift is accrued. This is expected from the analysis in Section II-E. which predicts a drift in master and slave positions due to modification of transmitted master velocity by slave PC. Additionally, it can be seen from the force plots in Fig. 9(b) that for the same master motion trajectory, the force reflection is reduced progressively. This is due to position drift, which results in progressively smaller penetrations by the slave into the remote environment. Similar trends are observed experimentally in Fig. 12, where the power-based TDPA was able to stabilize the bilateral teleoperation interaction but accumulated position drift. The operator was trying to apply a constant amount of force during each remote wall interaction, but it can be seen from Fig. 12(b) that the sensed environment force (f_e) is progressively decreasing. The operator had to move further every time to apply same force. This shows that with the power-based TDPA, it is not possible to apply a significant amount of force on the remote environment without severely compromising the position correspondence. In practical applications, it is desirable to be able to exert forces on the remote environment while maintaining a position correspondence between master and slave devices for meaningful telemanipulation.

The plots in Fig. 10 show simulation results from bilateral teleoperation using the power-based TDPA with r-passivity. There are a couple of important observations that can be made. First, the teleoperation interaction is stable, and position tracking between master and slave devices is recovered as seen in Fig. 10(a). The small steady-state error between x_m and x_s is due to Coulomb friction. The slave controller is effectively a *PD*-controller acting on position error, which will result in a steady-state error in the presence of friction. The steady-state error can be reduced by increasing λ, which will increase the effective proportional gain. Second, it can be observed from Fig. 10(b) that it was possible to apply consistent forces to the remote environment for the same master device trajectory. However, force reflection in free space motion is further degraded

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as compared to regular power-based TDPA due to the addition of FPCs. The experimental results shown in Fig. 13 support the observations made from simulations. The operator was able to apply consistent forces to the remote environment, and position synchronization was maintained.

Compared with the results from the power-based TDPA in [14], position drift between master and slave devices is eliminated. The transparency of teleoperation (similarity between operator and remote environment force) in the power-based TDPA, with or without r-passivity, is however degraded as compared to bilateral teleoperation using the energy-based TDPA [13], [24]. This conservatism in the power-based TDPA is because active behavior is never allowed, as opposed to the energy-based TDPA, where some active behavior is allowed until net stored energy in the system has been exhausted. The degradation of transparency due to feedback passivity control is evident even in frequency domain approaches, as reported in [19]. The use of the feedback passivity control approach imposes a tradeoff between degrading force-reflection performance and reducing the position drift between master and slave devices.

Coulomb friction in master and slave devices was not considered in the passivity analysis described in Section III, but simulations and experiments considering friction in Section IV. show stable teleoperation. This is expected because friction always dissipates energy, and hence contributes toward increasing passivity of the devices [25], [26]. Similar arguments could be made about the effect of friction on r-passivity of the devices, which is validated by the simulations and experiments demonstrating stable teleoperation.

The approach proposed in this paper successfully compensated the position drift inherent in power-based time domain passivity control of bilateral teleoperation, but there are some limitations. The parameter λ determines the ratio of proportional to derivative gains of the slave controller as described in Section III-B. A higher value of λ would mean stiffer position tracking and smaller steady-state error. However, choice of λ depends on the device and controller parameters as given by (21). A higher λ would require a higher B_i, which in turn will increase damping and deteriorate force reflection in free space motion. Proper tuning of the parameters λ and B_i requires knowledge of the device parameters (m_i and b_i). Without such information, B_i can be specified to be large so that the r-passivity conditions (21) are satisfied, but this would be overly conservative. Since most commercial haptic interfaces are equipped with only position sensors, there are practical limits on increasing the parameter B_i due to noise introduced by numerical differentiation of the position signal to compute velocity. This limits the range of λ that can be chosen such that r-passivity conditions are satisfied. Another limitation of our proposed approach is that the degradation of force reflection inherent in power-based TDPA still persists, which affects the overall transparency of the bilateral teleoperation.

One advantage of using the proposed approach is elimination of position drift inherent in bilateral teleoperation using the power-based TDPA. The power-based TDPA is a simple and easy to implement approach, but suffers from the problem of position drift. Position drift combined with the poor transparency due to the conservative nature of power-based TDPA renders the approach severely limited for useful practical applications. By eliminating position drift, the operator's control over the slave device is improved significantly, allowing the user to perform meaningful manipulation of the remote environment. It should be noted that our proposed extension to power-based TDPA is not intended as a technique for increasing the transparency of bilateral teleoperation. However, by extending the earlier power-based TDPA to P-MF teleoperation scheme, our approach has the advantage of masking the slave device dynamics from the user and improving transparency when the slave device has significant inherent dynamics (e.g., large geared industrial manipulators).

Position drift between master and slave devices is a common artifact of passivity-based bilateral teleoperation schemes. In TDPAs to bilateral teleoperation, modifications in commanded master velocity by the slave PC to enforce passivity of the communication channel are accumulated over time, resulting in position drift. A feedback passivity-control-based approach is proposed to encode position with the velocity signal, then transmitting this composite signal r over communication channel for compensating position drift in power-based time-domain passivity control of bilateral teleoperation systems. We show r-passivity of bilateral teleoperation under P-CF and P-MF architectures. Simulations and experiments conducted on a custom one DOF bilateral teleoperation setup demonstrate efficacy of our proposed approach under time-varying communication delays.

Appendix A

The power flow in TDPN combined with PC is given as

$$P^* = f_m v_m - f_s v_{sd}$$

and using (12) and (14), we can write

$$\begin{aligned} P^* &= (\hat{f}_m + \alpha v_m) v_m - (\hat{v}_{sd} + \beta f_s) f_s \\ &= (\hat{f}_m v_m - f_s \hat{v}_{sd}) + \alpha v_m^2 - \beta f_s^2 \\ &= (P_{\text{diss}} + \frac{dE}{dt}) + \alpha v_m^2 - \beta f_s^2 \text{ [by using (1) and (4)]} \\ &= (P_{\text{obs}}^L + \alpha v_m^2) + (P_{\text{obs}}^R - \beta f_s^2) + \frac{dE}{dt} \\ &= P_{\text{diss}}^* + \frac{dE}{dt}. \end{aligned}$$

It can be seen that the coefficients $\alpha(t)$ and $\beta(t)$ as defined in (13) and (15) ensure that $P_{\text{diss}}^* \geq 0$, which is the sufficient condition for ensuring passivity as discussed in Section II-B.

Appendix B

The r-passivity conditions are derived following the approach detailed in [20]. From (18), (19), and (20), the device dynamics augmented with feedback passivity control is given as

$$m_i \ddot{x}_i + (b_i + B_i)\dot{x}_i + K_i x_i = f_i + f_i^{\text{ext}}. \quad (24)$$

Now,

$$(f_i + f_i^{\mathrm{ext}})r = (m_i\ddot{x}_i + (b_i + B_i)\dot{x}_i + K_i x_i)(\dot{x}_i + \lambda x_i)$$
$$= \frac{dV(t)}{dt} + S(t)$$

where

$$V(t) = \frac{m}{2}\left[(\dot{x}_i + \lambda x_i)^2 + \left(\frac{\lambda(B_i + b_i) + K}{m} - \lambda^2\right)\right]$$

and $S(t) = \dot{x}_i^2(b_i + B_i - \lambda m_i) + \lambda x_i^2 K_i$.

It can be shown that under the conditions given by (21), $V(t) \geq 0$ and $S(t) \geq 0$. Hence, the devices are r-passive:

$$\int_0^t (f_i(\tau) + f_i^{\mathrm{ext}}(\tau))r(\tau)d\tau = V(t) - V(0) + \int_0^t S(\tau)d\tau \geq -V(0).$$

REFERENCES

[1] G. Niemeyer, C. Preusche, and G. Hirzinger, "*Telerobotics," in Springer Handbook of Robotics*. New York, NY, USA: Springer-Verlag, 2008, ch. 31.

[2] R. Anderson and M. Spong, "Bilateral control of teleoperators with time delay," *IEEE Trans. Autom. Control*, vol. 34, no. 5, pp. 494–501, May. 1989.

[3] R. J. Anderson and M. W. Spong, "Asymptotic stability for force reflecting teleoperators with time delay," *Int. J. Robot. Res.*, vol. 11, no. 2, pp. 135–149, 1992.

[4] H. K. Khalil, *Nonlinear Systems*, vol. 3. Upper Saddle River, NJ, USA: Prentice-hall, 2002.

[5] A. Haddadi and K. Hashtrudi-Zaad, "Bounded-impedance absolute stability of bilateral teleoperation control systems," *IEEE Trans. Hapt.*, vol. 3, no. 1, pp. 15–27, Jan./Mar. 2010.

[6] K. Hashtrudi-Zaad and S. E. Salcudean, "Analysis of control architectures for teleoperation systems with impedance/admittance master and slave manipulators," *Int. J. Robot. Res.*, vol. 20, no. 6, pp. 419–445, 2001.

[7] A. Haddadi, "Stability, performance, and implementation issues in bilateral teleoperation control and haptic simulation systems," Ph.D. dissertation, Dept. Electr. Comput. Eng., Queen's Univ., Kingston, ON, Canada, 2012.

[8] G. Niemeyer and J.-J. Slotine, "Stable adaptive teleoperation," *IEEE J. Ocean. Eng.*, vol. 16, no. 1, pp. 152–162, Jan. 1991.

[9] P. Arcara and C. Melchiorri, "Control schemes for teleoperation with time delay: A comparative study," *Robot. Auton. Syst.*, vol. 38, no. 1, pp. 49–64, 2002.

[10] P. F. Hokayem and M. Spong, "Bilateral teleoperation: An historical survey," *Automatica*, vol. 42, no. 12, pp. 2035–2057, 2006.

[11] E. Nuño, L. Basañez, and R. Ortega, "Passivity-based control for bilateral teleoperation: A tutorial," *Automatica*, vol. 47, no. 3, pp. 485–495, 2011.

[12] J. Ryu, D. Kwon, and B. Hannaford, "Stable teleoperation with time-domain passivity control," *IEEE Trans. Robot. Autom.*, vol. 20, no. 2, pp. 365–373, Apr. 2004.

[13] J. Ryu, J. Artigas, and C. Preusche, "A passive bilateral control scheme for a teleoperator with time-varying communication delay," *Mechatronics*, vol. 20, no. 7, pp. 812–823, 2010.

[14] Y. Ye, Y.-J. Pan, and T. Hilliard, "Bilateral teleoperation with time-varying delay: A communication channel passification approach," *IEEE/ASME Trans. Mechatronics*, vol. 18, no. 4, pp. 1431–1434, Aug. 2013.

[15] D. Lee and M. W. Spong, "Passive bilateral teleoperation with constant time delay," *IEEE Trans. Robot.*, vol. 22, no. 2, pp. 269–281, Apr. 2006.

[16] J. Artigas, J. Ryu, C. Preusche, and G. Hirzinger, "Network representation and passivity of delayed teleoperation systems," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2011, pp.177–183.

[17] J. Artigas, J. Ryu, and C. Preusche, "Time domain passivity control for position-position teleoperation architectures," *Presence, Teleoperators Virtual Environ*, vol. 19, no. 5, pp. 482–497, 2010.

[18] N. Chopra, M. W. Spong, S. Hirche, and M. Buss, "Bilateral teleoperation over the internet: The time varying delay problem," in *Proc. Amer. Control Conf.*, 2003, pp. 168–173.

[19] N. Chopra, M. W. Spong, and R. Lozano, "Synchronization of bilateral teleoperators with time delay," *Automatica*, vol. 44, no. 8, pp. 2142–2148, 2008.

[20] D. Lee and D. Xu, "Feedback r-passivity of lagrangian systems for mobile robot teleoperation," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2011, pp. 2118–2123.

[21] I. G. Polushin, P. X. Liu, C.-H. Lung, and G. Dien On, "Position-error based schemes for bilateral teleoperation with time delay: Theory and experiments," *J. Dyn. Syst., Meas., Control*, vol. 132, no. 3, pp. 031008-1–031008-11, 2010.

[22] E. Rodriguez-Seda and M. Spong, "A time-varying wave impedance approach for transparency compensation in bilateral teleoperation," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2009, pp. 4609–4615.

[23] K. J. Kuchenbecker, J. G. Park, and G. Niemeyer, "Characterizing the human wrist for improved haptic interaction," in *Proc. ASME Int. Mech. Eng. Congr. Expo.*, 2003, vol. 2, pp. 42017–42025.

[24] J. Artigas, J. Ryu, and C. Preusche, "Position drift compensation in time domain passivity based teleoperation," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2010, pp. 4250–4256.

[25] J. Abbott and A. Okamura, "Effects of position quantization and sampling rate on virtual-wall passivity," *IEEE Trans. Robot.*, vol. 21, no. 5, pp. 952–964, Oct. 2005.

[26] J. Kim, C. Seo, J. Ryu, and J. Kim, "Enhancing rate-hardness of energy-bounding algorithm by considering coulomb friction of haptic interface," in *Proc. IEEE Haptics Symp.*, 2010, pp. 157–160.

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