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Bilateral Delayed Teleoperation: The Effects of a Passivated Channel Model and Force Sensing

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***Abstract*— In this paper, based on a passivity framework, admittance-type and hybrid-type delay-compensated communication channel models are introduced, which warrant different bilateral control architectures for wave-based teleoperation under time delay. We utilize wave transforms and signal filtering for passivating the delayed-communication channel and passivity/stability conditions are derived using scattering theory based on an end-to-end model of the teleoperation system rather than the communication channel alone. Contrary to a commonly held view, it is proven that the teleoperation system can remain stable when force measurement data of the master and the slave manipulators interactions with the operator and the remote environment are used. Experimental results on a soft-tissue task for a hybrid-type architecture and for round-trip delays of 60 msec and 600 msec show that using slave-side force measurements considerably enhances teleoperation transparency.**

I. INTRODUCTION

The main goals of teleoperation are stability and transparency. Transparency is the ability of a teleoperation system to present the undistorted dynamics of the remote environment to the human operator. The ability to do so is affected by the closed-loop dynamics of the master and the slave robots, which distort the dynamics of the remote environment as perceived by the human operator [1], [2], [3]. Among the more relevant aspects of teleoperation is an interesting control problem resulting from the presence of a non-negligible time delay in the communication media between the master and the slave. In the presence of time delays, the stability and transparency of a bilateral teleoperation system are severely affected. Several approaches have been proposed in the literature to deal with this problem. For a comprehensive overview and comparison on various time delay compensation methods, one can refer to [4]. Scattering theory and its intuitively reformulated derivation, the wave transformation approach, are theoretically capable of achieving stability independent of time delays [5], [6]. Both of these approaches are based on passivity, which is a sufficient condition for stability. The key issue for these approaches is to make the non-passive communication medium with time delay passive.

The main contributions of this paper are as follows: In order to carry out an in-depth study of stability and transparency of a teleoperation system in the presence of time delay, we extend the passivity-based approach proposed in [5] and introduce admittance-type and hybrid-type two-port network models based on different choices of wave transformation arrangements, which warrant different teleoperation control architectures. In both cases (admittance-type and hybrid-type), the teleoperation system configuration is affected by the presence or absence of force sensing in the system. Stability of the proposed configurations is examined using passivity-framework analysis of the teleoperation system. Contrary to a commonly held view that using force sensors is not desirable due to its negative effect on stability, we show that stability can be maintained in the presence of force sensing and derive conditions for robustly stable operation of different configurations. It is shown that for haptic teleoperation applications, it is better for practical reasons to use a hybrid-type configuration instead of an admittance-type one. We demonstrate that using direct force measurements does not necessarily render a delayed hybrid-type teleoperation system unstable. Moreover, it is shown that slave-side force measurements improve transparency compared to position error-based approaches. The theories proposed here are supported with experimental results based on a haptic teleoperation test-bed for minimally invasive surgery for two different values of round-trip time delays of 60 and 600 ms.

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II. PASSIVITY AND ROBUST STABILITY

Assume the following equations of motions for the master and the slave manipulators:

$$M_m \ddot{x}_m = -f_m + f_h \qquad M_s \ddot{x}_s = f_s - f_e \tag{1}$$

where M_m and M_s are the master and slave inertias, f_m and f_s are the master and slave control actions, and x_m and x_s are the master and slave positions. Also, f_h and f_e represent the interaction forces between the operator's hand and the master, and the slave and the remote environment respectively.

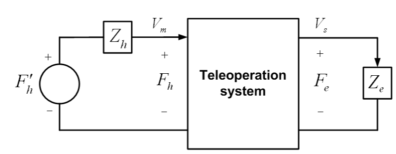

Fig. 1. Equivalent circuit representation of a teleoperation system.

By considering velocities and forces in a teleoperation system as currents and voltages, an equivalent circuit representation of the system can be obtained (Figure 1), in which impedances $Z_h(s)$, $Z_m(s) = M_m s$, $Z_s(s) = M_s s$, and $Z_e(s)$ denote the dynamic characteristics of the human operator's arm, the master robot, the slave robot, and the remote environment, respectively. Also, f_h' is the exogenous input force from the operator. This equivalent circuit representation can be expressed by the following hybrid model:

$$\begin{bmatrix} F_h \\ -V_s \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \cdot \begin{bmatrix} V_m \\ F_e \end{bmatrix}$$

A. Scattering theory and stability robustness

According to Colgate [7]: *A bilateral teleoperation system is said to be robustly stable if, when coupled to any passive environment, it presents to the operator an impedance (admittance) which is passive.* It is generally assumed that the human operator is passive, i.e., the operator does not perform actions to make the system unstable. Based on its scattering matrix model, a teleoperation system is represented as $b = S(s)a$ where $a = [a_1 \quad a_2]^T$ and $b = [b_1 \quad b_2]^T$ are input and output waves of the teleoperation system, respectively. In a general two-port network, the relation between input and output waves and equivalent voltages and currents can be expressed as $a = (F + n^2V)/2$ and $b = (F - n^2V)/2$ where $F = [F_h \quad F_e]^T$ and $V = [V_m \quad -V_s]^T$ are the two-port's equivalent voltage and current vectors in the s domain, and n is a scaling factor. In a reciprocal network, we have $S_{12} = S_{21}$ and in a symmetric network $S_{11} = S_{22}$. In [7], it has been shown that a necessary and sufficient condition for robust stability of a teleoperation system is

(a) $S(s)$ contains no poles in the closed right half plane (RHP), and

(b) if Δ is the structured perturbation of S

$$\sup_\omega[\mu_\Delta(S(j\omega))] \leq 1 \tag{2}$$

where $\mu_\Delta(S)$ is the structured singular value of S. A useful property for $\mu_\Delta(S)$ is [7]:

$$\mu_\Delta(S) \leq \bar{\sigma}(S) \tag{3}$$

where $\bar{\sigma}(S)$ is the maximum singular value of S. with the equality holding if the network is reciprocal [8]. The condition (b) for robust stability is equivalent to the passivity of S (i.e., $\bar{\sigma}(S) \leq 1$). The smaller $\bar{\sigma}(S)$ is for a teleoperation system, the larger are the stability margin of the system and the stability robustness of the closed-loop system against variations in the dynamic parameters of the master, the slave and the controller.

B. Passivity-based time delay compensation

In the presence of a time delay, an ideally transparent bilateral teleoperation system has the following pair of hybrid and scattering matrices:

$$H = \begin{bmatrix} 0 & e^{-sT} \\ -e^{-sT} & 0 \end{bmatrix} \quad S = \begin{bmatrix} -\tanh(sT) & \mathrm{sech}(sT) \\ \mathrm{sech}(sT) & \tanh(sT) \end{bmatrix} \tag{4}$$

It can be shown that $\bar{\sigma}(S)$ for this scattering matrix is unbounded, consequently this system cannot maintain stability. In practice, stability and transparency are competing issues in a teleoperation system [1]. Therefore, one can intuitively argue that $\bar{\sigma}(S) = 1$ is the optimum choice for maintaining stability while the system operates with the best achievable transparency possible. A physical interpretation for a two-port network with $\bar{\sigma}(S) = 1$ is the ideal transmission line with time delay, which can be represented by the following pair of hybrid and scattering matrices:

$$H = \begin{bmatrix} \tanh(sT) & \mathrm{sech}(sT) \\ -\mathrm{sech}(sT) & \tanh(sT) \end{bmatrix} \quad S = \begin{bmatrix} 0 & e^{-sT} \\ e^{-sT} & 0 \end{bmatrix} \tag{5}$$

Comparing equations (4) and (5), it can be seen that in the delayed transmission line, stability has been attained at the expense of degraded transparency. Based on this argument, the following control law was proposed in [5], which passivates a communication channel with time delay in a two-channel bilateral teleoperation system:

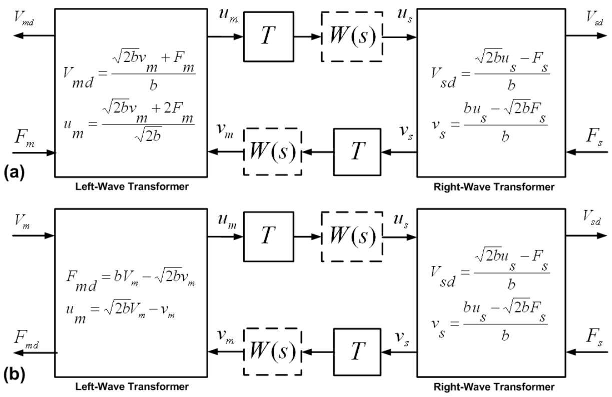

Fig. 2. (a) Admittance-type and (b) hybrid-type delay-compensated communication channels.

$$\begin{aligned} F_{md} &= F_s e^{-sT} + n^2(V_m - V_{sd}e^{-sT}) \\ V_{sd} &= V_m e^{-sT} + n^{-2}(F_{md}e^{-sT} - F_s) \end{aligned} \tag{6}$$

An energy-based approach, which yields the same results in a more physically-motivated manner, was proposed in [6]. A pair of wave variables (u, v) is defined, based on a pair of standard power variables $(\dot{x}, f)$, by the following:

$$u = \frac{b\dot{x} + f}{\sqrt{2b}} \qquad v = \frac{b\dot{x} - f}{\sqrt{2b}} \tag{7}$$

where u denotes the right moving wave while v denotes the left moving wave. The characteristic wave impedance b is a positive constant and assumes the role of a tuning parameter. Depending on the choice of input/output pairs from the four variables in equations (7), we distinguish four different wave transformation arrangements. These four passivity-based time delay compensation architectures are position-force (i.e. position control at the master side and force control at the slave side), force-position, position-position, and force-force. Among these four architectures, in order to have a stiff slave, we are interested in the two cases in which the slave is under position control, namely position-position or *admittance-type delay-compensated channel* (Figure 2a) and force-position or *hybrid-type delay-compensated channel* (Figure 2b). In both architectures, the time delay T has been assumed to be constant and equal in both directions. In the admittance-type delay-compensated channel, the master and the slave velocities have been taken as outputs of the overall two-port network. In the hybrid-type, however, the slave velocity and the force transmitted to the master side are outputs.

In practice, a wave-based teleoperation system performance can be degraded due to a number of reasons, among which are discrete implementation of continuous-time control laws and significant variations in the operator's behavior or the environment impedance. The performance is particularly degraded for large time delays where high frequency oscillations appear in the teleoperation system. The idea of filtering the wave variables (wave-domain lowpass filtering) was initially suggested in [6] for noise reduction and frequency shaping, specially when the proposed impedance matching scheme fails to achieve the goal of transparency

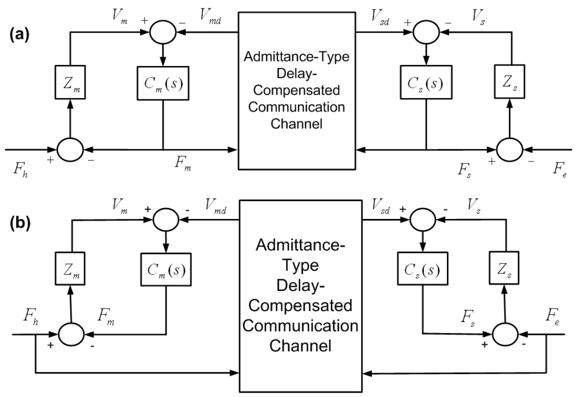

Fig. 3. Wave-based admittance-type teleoperation systems: (a) APEB; (b) AKFB.

improvement. In continuation of this work, [9] compared the performance of impedance matching and wave filtering. In this research, we use lowpass filters $W(s)$ in the wave domain according to Figure 2 and draw the corresponding stability conditions.

III. ADMITTANCE-TYPE CONFIGURATIONS

A. APEB and filtered APEB

A wave-based Admittance-type Position-Error Based (APEB) teleoperation system is illustrated in Figure 3a. In this system, let us take $M_m = M_s = M$ and PD position controllers $C_m(s) = C_s(s) = (k_d s + k_p)/s$ used at the master and the slave. The resulting teleoperation system has a scattering matrix that is both reciprocal and symmetric. As a result, investigating system stability using criteria (a) and (b) given in Section II.A is analytically tractable.

In the neighbourhood of $T = 0$ (fairly small time delays), by using a first order Pade approximation for the exponential terms in the characteristic polynomial of the S matrix, it can be inferred that the sufficient condition for S to be RHP analytic is $k_d > 0$ and $k_p > 0$. The singular values of the scattering matrix for the APEB teleoperation system are:

$$\sigma_1, \sigma_2 = \left| \frac{(A_1 - B_1 + C_1 - D_1)e^{-sT} \pm (A_1 + B_1 - C_1 - D_1)}{(A_1 - B_1 - C_1 + D_1)e^{-sT} \pm (A_1 + B_1 + C_1 + D_1)} \right| \tag{8}$$

where $A_1 = Mbs^2 + bk_d s + bk_p$, $B_1 = Ms(k_d s + k_p)$, $C_1 = k_d s + k_p$ and $D_1 = bs$. Therefore, condition (b) for stability leads to:

$$2b^2 k_d \omega^2 [1 \pm \cos(\omega T)] \geq 0 \tag{9}$$

Since $k_d > 0$, both of the inequalities in (9) hold regardless of ω or T. If wave-domain low pass filters are utilized in the APEB teleoperation system, the stability conditions will be (a) $k_d > 0$ and $k_p > 0$ as sufficient conditions, and (b) the singular values of the new scattering matrix will be the same as (8) if e^{-sT} is replaced by $e^{-sT}W(s)$, giving the following stability condition:

$$\frac{L^2[k_d \omega^2 (b + k_d) + k_p^2] + 2bk_d}{2bk_d\sqrt{1 + L^2}} \geq |\cos(\omega T + \varphi)| \tag{10}$$

where $\tan(\varphi) = L$, $W(s) = (Ls + 1)^{-1}$, $L = (2\pi f_{\text{cut}})^{-1}$, and f_{cut} is the cut-off frequency of the first-order lowpass filters. The above condition defines a region of stability for a filtered APEB teleoperation system. For $L = 0$, (10) simplifies to (9).

B. AKFB and filtered AKFB

Both Anderson and Spong [5] and Niemeyer and Slotine [6] have avoided the use of force sensor measurements in bilateral teleoperation control due to their inherent noisy nature and questions which may rise about the passivity of the whole system. In this paper, a new two-channel wave-based teleoperation architecture is proposed which uses force sensing at both the master and the slave ends. In this section, we show that incorporating force sensor measurements in a time-delay teleoperation control algorithm does not necessarily destablize the system and we derive corresponding robust stability conditions. Figure 3b depicts a wave-based Admittance-type Kinesthetic Force Based (AKFB) teleoperation configuration, in which measurements of hand-master and slave-environment interaction forces are used. Due to reciprocity and symmetry of its scattering matrix, an AKFB teleoperation system can be studied analytically. Similar to the APEB configuration, a sufficient condition set for meeting criterion (a) is $k_d > 0$ and $k_p > 0$. For criterion (b),

$$\sigma_1, \sigma_2 = \left| \frac{(A_2 + B_2 - C_2)e^{-sT} \pm (A_2 - B_2 - C_2)}{(A_2 - B_2 + C_2)e^{-sT} \pm (A_2 + B_2 + C_2)} \right| \tag{11}$$

where $A_2 = Mbs^2 + bk_d s + bk_p$, $B_2 = k_d s + k_p$, and $C_2 = bs$. The stability condition is given by

$$\frac{b}{\sqrt{b^2 + \omega^2 M^2}} \geq |\cos(\omega T - \varphi)| \tag{12}$$

where $\tan(\varphi) = \omega M/b$. In this configuration, the region of stability is more limited in comparison to APEB. However, robust stability can be achieved through proper selection of system parameters. For instance, choosing the system's parameters such that $\omega M \ll b$ sufficiently ensures criterion (12). If we make use of lowpass filters in AKFB, the singular values of the new scattering matrix can be obtained from (11) through replacing e^{-sT} with $e^{-sT}W(s)$. In this way, the corresponding stability condition set is:

$$\frac{\omega^2 L^2 (bk_d - Mk_p + k_d^2) + L^2 k_p^2 + 2bk_d}{2k_d\sqrt{(1 + \omega^2 L^2)(b^2 + \omega^2 M^2)}} \geq |\cos(\omega T - \varphi)| \tag{13}$$

where $\tan(\varphi) = \omega(M - bL)/(M\omega^2 L + b)$. Similar to (12), (13) can be also satisfied through proper choice of the relevant parameters.

C. Implementation issues

Our interest in hybrid-type teleoperation configurations stems from a tuning disadvantage of the admittance-type configurations. From the controller tuning point of view, assuming an APEB teleoperation system without time delay, the closed-loop control law at the slave side is

$$M_s s^2 E + C_s E = F_e \tag{14}$$

where $E = X_m - X_s$ and $C_s = k_{ds} s + k_{ps}$. Obtaining the similar equation for the master side and subtracting the two equations gives:

$$(M_m - M_s)s^2 E + (C_m - C_s)E = F_h - F_e \tag{15}$$

In the ideal case $F_h = F_e$, hence

$$s^2 E + \frac{C_m - C_s}{M_m - M_s} E = 0 \tag{16}$$

If we assume $(C_m - C_s)/(M_m - M_s) = C$ is a PD controller to ensure asymptotic convergence of $e(t)$ to zero, then we can simply choose the master and the slave PD controllers as $C_m = M_m C$ and $C_s = M_s C$, resulting in:

$$C_m/M_m = C_s/M_s \tag{17}$$

Based on (17), the slave-side PD controller is tuned for tracking under the free motion condition, and the master-side controller will be a scaled version of that. The ultimate goal of tuning in a bilateral teleoperation system is to make the slave controller as ”stiff” as possible, while keeping the master as “compliant” as possible. However, by making the slave controller stiff through increasing its gains, according to (17), the outputs of the master and the slave controllers can saturate causing high-frequency vibrations in the system. On the other hand, excessive reduction of the slave controller gains will cause underdamped (and low-frequency oscillatory) response. In practice, it was observed that for the haptic teleoperation system that we used in our experiments the range of the slave controller's gains for which saturation of the master and the slave controllers are avoided corresponds to a dominant pole location that leads to a very compliant and underdamped slave.

IV. Hybrid-type Configurations

Hybrid-type configurations of teleoperation systems do not have the tuning problems of admittance-type configurations. Figure 4 shows filtered HPEB and HKFB teleoperation systems. Due to the asymmetric nature of the corresponding scattering matrices, stability analysis of neither of these configurations is mathematically tractable as was the case with the symmetric networks. In their pioneering work on passivity-based time delay compensation in a bilateral teleoperation system, Anderson and Spong introduced a preliminary model of the HPEB teleoperation configuration and based their proof of stability on modeling this system as a cascade of passive two-port networks [5]. This approach uses the fact that the cascade interconnection of any two passive systems is passive. The problem with the cited approach is that it cannot be extended to the case of an HKFB teleoperation system in a straightforward manner. A rigorous stability study of the HKFB architecture needs more developments and cannot be adequately addressed in this limited space.

It is worth mentioning that the HKFB architecture possesses a scattering matrix, which is neither symmetric nor reciprocal implying that, although sufficient, passivity is not a necessary condition for its stability. The interest in passivity of a teleoperation system stems from the fact that it ensures robustly stable performance for a class of multivariable systems that cannot be easily subjected to other methods of stability analysis, usually at the cost of performance.In practice, it was observed that by utilizing two additional lowpass filters in the system, one for filtering the measured slave/environment interaction force f_e before feeding it to the slave-side wave transformer and the other for filtering the reflected force f_{md} before applying it to the master robot, according to Figure 4b, it is possible to have better loop-shaping flexibility in order to obtain the best stable performance in the teleoperation system. It can be shown that even in the absence of any force sensor noise, these low-pass filters help to improve transparency by pushing the maximum singular values of the scattering matrix of

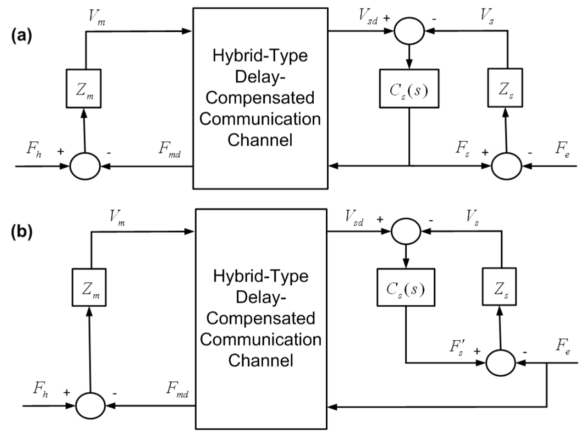

Fig. 4. Wave-based hybrid-type teleoperation systems: (a) HPEB; (b) HKFB.

the HKFB teleoperation system towards unity. The precise tuning of these filters depends on the characteristic of the force sensor and is basically an implementation issue.

A. Experimental Performance Evaluation

For experimental evaluation, we have used a force-reflective master-slave system developed as an endoscopic surgery test-bed (Figure 5). Through the master interface, a user controls the motion of the slave surgical tool and receives force/torque feedback of the slave-environment interactions [10]. In the haptic master interface, the friction/gravity effects are determined and compensated for such that the user does not feel any weight on his/her hand when the slave is not in contact with an object. The Virtual Reality Peripheral Network (www.vrpn.org) has been used for network-based communication such that the slave can be telemanipulated from the master. Circular buffers have been used to create adjustable time delays in the communication channel. In the experiments, the master and slave subsystems were constrained for force-reflective teleoperation in the twist direction only (i.e., rotations about the instrument axis). In order to perform a soft-tissue palpation task with this 1-DOF setup, the user manipulates the master causing the slave to probe the tissue via a small rigid beam attached to the endoscopic instrument. The user then moves the master back and forth for 100 seconds. For these palpation tests, we used an object made of packaging foam material.

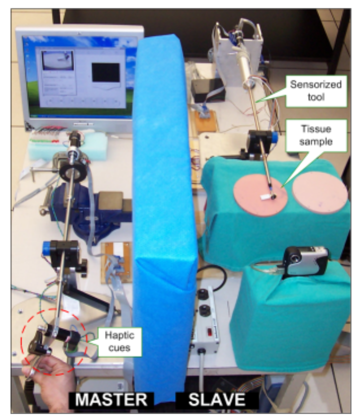

Fig. 5. Setup for telemanipulated tissue palpation.

Figure 6 shows the master and the slave position and torque tracking profiles for an HPEB teleoperation system implementation with $M_m = 5.968 \times 10^{-4}$ kgm^2, $M_s = 9.814 \times 10^{-3}$ kgm^2, $b = 1$, $T = 30$ ms, $k_d = 3$, $k_p = 10$, and $f_{\text{cut}} = 5$ Hz. This amount of time delay corresponds to the typical delay experienced in the terrestrial wired telecommunication link used for the telesurgery experiments reported in [11]. Figure 7 illustrates the same tracking profiles for a modified HKFB teleoperation system with similar parameters, where the cut-off frequency for f_e and f_{md} first-order filters is 2 Hz. As can be deduced from these figures, the position tracking performance for the two systems are close to each other. However, the modified HKFB teleoperation system displays a superior force tracking performance, which demonstrates a higher level of transparency. This deduction is in accordance with the results presented in [12] for teleoperation systems without time delay. To further investigate the relative transparency of these two systems, a second set of free-motion tests was performed, which in conjunction with the previous contact-mode tests, can be used to determine the hybrid parameters of the teleoperation system in the frequency domain. In the free-motion tests, the master is moved back and forth by the user for about 100 seconds, while the slave's tip is in free space. Since $f_e = 0$, the frequency response $h_{11} = F_h/X_m$ and $h_{21} = -X_s/X_m$ can be found by applying spectral analysis (MATLAB function *spa*) on the free-motion test data (for the two-port hybrid model based on positions and forces). By using the contact-mode test data, the other two hybrid parameters can be obtained as $h_{12} = F_h/F_e - h_{11}X_m/F_e$ and $h_{22} = -X_s/F_e - h_{21}X_m/F_e$. The magnitudes of the hybrid parameters of the HPEB and HKFB teleoperation systems for $T = 30$ ms are shown in Figure 8. Due to the human operator's limited input bandwidth, these identified hybrid parameters can be considered valid up to frequency 100 rad/s. Figure 8 is an indication of HKFB's superiority in terms of transparent performance considering the ideal transparency requirements outlined by (4). The hybrid parameter $h_{11} = F_h/X_m|_{F_e=0}$ is the input impedance in free-motion condition. High values of h_{11} for HPEB are evidence of the fact that even when the slave is in free space, the user will feel some force as a result of any control inaccuracies (i.e., nonzero position errors), thus giving a "sticky" feel of free-motion movements. On the other hand, since HKFB uses f_e measurements, its input impedance in free-motion condition will be significantly lower making the feeling of free space much more realistic. The parameter $h_{12} = F_h/F_e|_{X_m=0}$ is a measure of force tracking for the haptic teleoperation system. The better force tracking performance of HKFB in Figure 8, i.e., $h_{12} \approx 0$ dB, confirms the time-domain results observed in Figures 6 and 7. The parameter $h_{21} = -X_s/X_m|_{F_e=0}$ is a measure of the position tracking performance. In this respect, both spectra are close to 0 dB, which indicates both systems ensure good position tracking. It is worthwhile mentioning that because of the finite stiffness of the slave and also the backlash present in the slave's gearhead, the accuracy of $h_{22} = -X_s/F_e|_{X_m=0}$ estimates is less than that of the rest of the hybrid parameters.

In order to study the transparency of the two teleoperation systems under larger time delays, the same experiments were repeated for $T = 300$ ms. This is a typical upper bound for a single-hop satellite link's time delay [11]. Figure 9 and Figure 10 show the position and force tracking profiles for the HPEB and HKFB teleoperation systems respectively. Figure 11 shows the hybrid parameters for these two systems. As can be seen in Figure 9, with HPEB bilateral control, there are vibrations in the master and slave positions and forces in the contact mode (with the magnitudes of vibrations increasing with time delay). While stability in the wave-based time delay compensation approach is guaranteed in theory regardless of the time delay, in practice and consistent with previous studies [5], [6], [13], such vibrations exist and may be due to implementation reasons such as discretization or limited controller bandwidth. As can be seen in Figure 11, these vibrations affect the h_{12} parameter of the HPEB teleoperation system. However, as shown in the force profile of Figure 10 and the h_{12} spectrum of Figure 11, force tracking is much less subjected to unwanted vibrations in the case of HKFB. These results are indicative of the fact that transparency is improved by provision of slave force sensor data to the bilateral control algorithm.

V. CONCLUSION

In this paper, we have provided analysis tools for examining stability and transparency of teleoperation systems. The concept of passivity-based time delay compensation has been extended to two two-port network architectures, admittance-type and hybrid-type. It was shown that using any of these two time-delay compensated channel architectures, stable teleoperation systems can be implemented, with or without direct force measurements. It was also demonstrated that in practice it is better to use a hybrid-type control architecture because simultaneous tuning of the two PD controllers in the admittance-type architecture can be problematic. Moreover, from the point of view of transparency, the use of force sensors provides better performance. Experimental results with 60 ms and 600 ms round-trip delays showed that using a force sensor at the slave side significantly improves transparency of the passivity-based teleoperation system.

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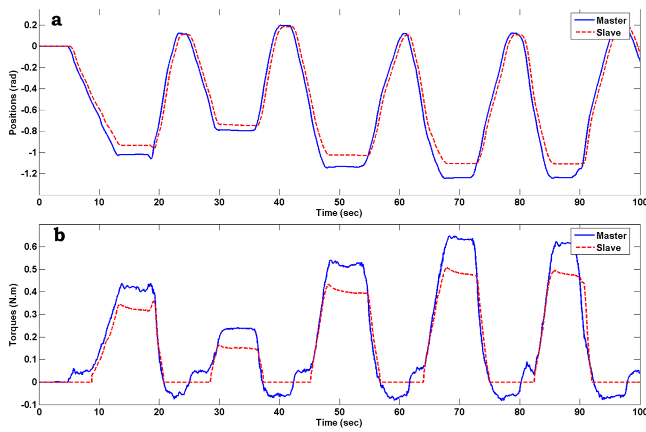

Fig. 6. (a) Position and (b) force tracking profiles for the HPEB teleoperation system with one-way delay $T = 30$ ms.

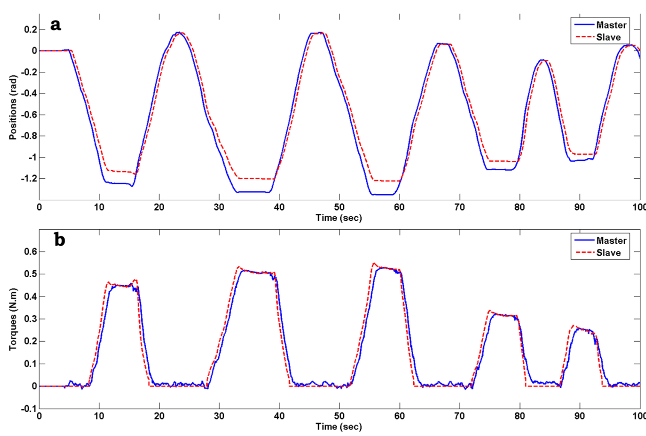

Fig. 7. (a) Position and (b) force tracking profiles for the HKFB teleoperation system with one-way delay $T = 30$ ms.

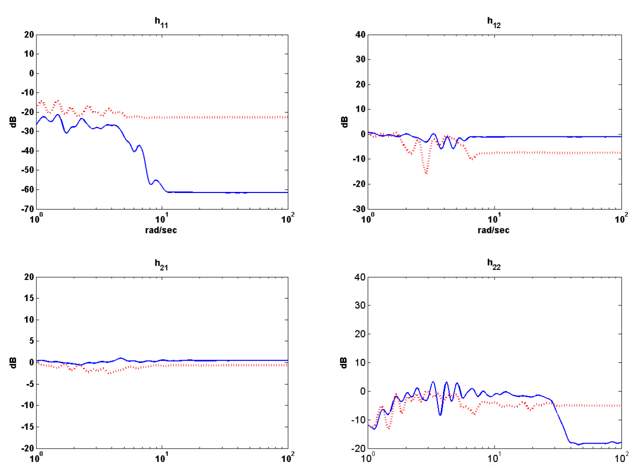

Fig. 8. Magnitudes of the hybrid parameters for the HPEB and HKFB teleoperation systems with one-way delay $T = 30$ ms (dashed: HPEB; solid: HKFB).

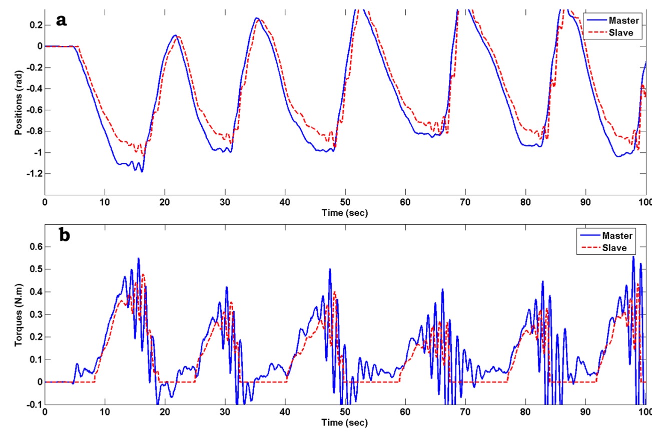

Fig. 9. (a) Position and (b) force tracking profiles for the HPEB teleoperation system with one-way delay $T = 300$ ms.

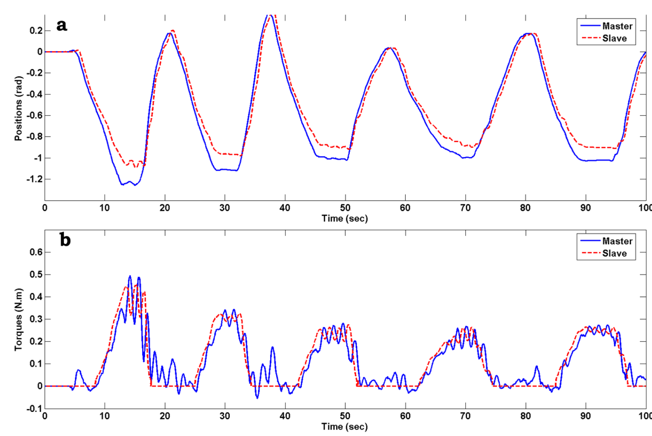

Fig. 10. (a) Position and (b) force tracking profiles for the HKFB teleoperation system with one-way delay $T = 300$ ms.

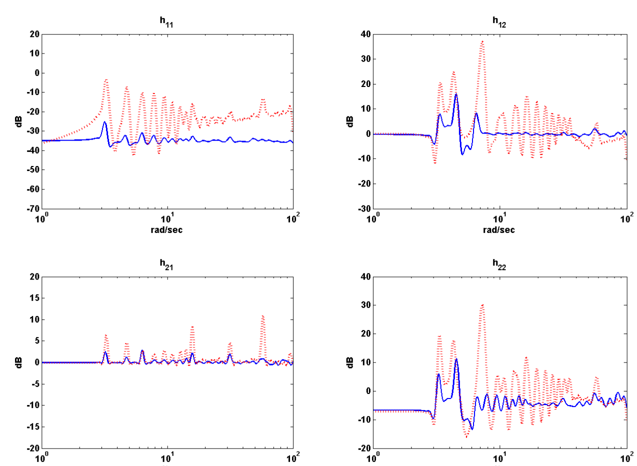

Fig. 11. Magnitudes of the hybrid parameters for HPEB and HKFB teleoperation systems with one-way delay $T = 300$ ms (dashed: HPEB; solid: HKFB).