A Passivity-Shortage Based Control Design for Teleoperation With Time-Varying Delays

Deepalakshmi Babu Venkateswaran and Zhihua Qu

Abstract—**This letter investigates the effect of time-varying delays in bilateral teleoperation, with respect to stability and performance, using the properties of passivity-shortage. Until recently, the desired stability and performance characteristics were achieved using the concept of passivity. However, passivity is limited to systems of relative degree zero or one, while passivity-shortage includes systems of higher relative degrees and possibly of non-minimum phase. Passivity-shortage also arises naturally when data transmission is subject to delays, either constant or time-varying. In this letter, the properties of passivity-shortage are employed to design a simple negative feedback controller. We show that the proposed method provides a faster responding solution and improved performance compared to the existing approaches. The performance improvements include improved steady-state error convergence, and robustness against environmental disturbances, even in the presence of varying delays.**

Index Terms—**Telerobotics and teleoperation, passivity-based control, passivity-short systems, position control.**

I. Introduction

Bilateral teleoperation is a two-way communication and coordination framework between master and slave robotic systems (Fig. 1). The input and output information such as position, velocity, and torque is communicated back and forth between the two systems. The master robot (which could be either physical or virtual) is controlled by a human operator based on the feedback from both the robots. The slave robot gets its input from the master robot and the environment. The goal of teleoperation is to make the slave robot coordinate with the master robot, to either replicate its actions or to work together.

The communication channel between the robots may incur delays that can cause performance degradation and even instability in teleoperation systems. Furthermore, time-varying delays can stretch or compress signals and increase position error between the two robots, thereby degrading the performance of teleoperation [1].

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The authors are with the Department of Electrical and Computer Engineering, University of Central Florida, Orlando, FL 32816 USA (e-mail: deepababu@knights.ucf.edu; qu@ucf.edu).

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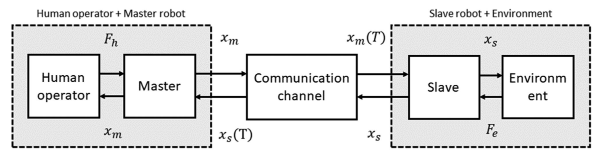


Fig. 1. Bilateral Teleoperation.

The issue of instability and performance caused by time delays is addressed by designing an appropriate controller. Over the past decade, several controls were reported for systems with either small or large delays. In the case of large delays, the so-called virtual environment based approach, such as [2]–[5], was used to generate new models for teleoperation scenarios, but no stability proof was reported. The stability proof is generally based on the passivity properties of robot dynamics (from torque input to velocity output). A detailed survey of the existing passivity based approaches is provided in [6], [7]. The classical approaches to stability proof include two-port scattering transformation, i.e., the linear transformation of input-output signals to wave variables [8], [9], force reflecting algorithm using wave variable based four-channel [10], [11], time-domain passivity approach (TDPA) [12], [13]. All of the above methods address stability issues related to delays by passifying the communication channel under the de-facto assumption that the robot dynamics are passive.

It is interesting to note that most systems in real life are not passive since passivity is very restrictive. It requires the system to be of minimum phase with relative degree equal to zero or one. Specifically, the robot dynamics is not passive in the position-force domain for all frequency ranges [14]–[16]. Even when the system is not linear and not passive, many methods aim to correct the uncertainties to make the master and slave system passive, such as integral quadratic constraints (IQC) [17]–[19]. It works by compensating for the delay in the communication channel, saturation and monotone nonlinearity of the environment by considering them as a separate block connected in negative feedback with the linear passive system by using appropriate multipliers to make the overall system passive and compensate for the lack of passivity, by introducing an excess of passivity. Other studies include [20], where a neural network is proposed to eliminate the dynamic uncertainties of the systems, [21] eliminates the constraints on the varying delay using adaptive laws, [22] introduces a switching control to guarantee the passivity of teleoperation, with position feedback to improve their tracking performance. Stability proof of all these approaches requires the overall system to be passive.

In addition, there exist studies in the position-force domain that does not make any passivity assumptions. In [23], adaptive control is used to design stable bilateral teleoperation using a functional differential equation approach. A high-gain velocity observer is used in [24], to show the convergence of position error, in the presence of time delays. PD-like controllers are used in [25], where the solutions of linear matrix inequalities are used to analyze the stability, [26] uses the same approach with the terminal sliding mode controller to estimate its velocity. In these existing approaches, the knowledge of the dynamics of the system is required to design the controller.

An alternate dissipativity-based teleoperational framework based on the concept of passivity-shortage is proposed in [15], which can employ systems of higher-order (with relative degree zero, one and more). Passivity-shortage is an extension of passivity, where the system under consideration is energetically bounded by input-output power, input energy and output energy (instead of just input-output power as in the case of passive systems) [27]. In [28]–[30], passivity-shortage-based semi-autonomous human-robot swarm interconnection is discussed, and the authors observe the tendency of the human operator to lose passivity and become passivity-short in various scenarios such as network delay when the inter-robot network is sparse [29], when the human operator is not trained enough [30], especially when the network includes multiple slave robots. The insufficiency of passivity has been well established in recent literature, but only a little information is evident about what lies beyond passivity.

Our primary goal is to develop a teleoperation framework that guarantees both stability and good performance (in the sense of position tracking) that works beyond passivity. This letter extends the results of our earlier conference version [15] by considering both time-varying communication delays and robot-environment interactions. The highlights of the results shown in this letter are as below. In essence,

1) varying time-delays by nature are passivity-short,
2) appropriate feedback interconnections of passivity-short systems can guarantee L_2 stability of the overall system in the presence of environmental disturbances and varying time delay.
3) Experimental results (using Phantom Omni devices) show that the proposed approach has less chattering and improved steady-state error convergence compared to the existing approaches.

The rest of the letter is organized as follows: A brief overview of passivity-short systems, their properties, and the problem statement are given in Section II. Two different configurations of passivity-short systems are investigated, and their stability conditions are developed in Section III. The performance of the proposed feedback control method is analyzed in Section IV to show that the proposed method has better performance in terms of phase lag and steady-state error when compared to the existing methods. Section V provides the experimental results, and they agree with the results from the earlier sections.

II. Preliminaries

Consider the following general class of dynamic systems:

$$\begin{aligned} \dot{x} &= f(x,u), \quad x(0) = x_0, \\ y &= h(x,u), \end{aligned} \tag{1}$$

where $u \in \Re^m$, $x \in \Re^n$, and $y \in \Re^p$. Dynamic mapping $\mathcal{P}$ of system (1) denotes the input-output mapping from input u to output y. Mapping $\mathcal{P}$ can be analyzed and characterized generally using the dissipativity theory [31] or, more specifically, the passivity-short property [27] defined below (often coupled with an appropriately designed feedback control).

Definition: Dynamic mapping $\mathcal{P}$ of system (1) is said to be *input passivity-short* or simply *passivity-short* if there exists a positive definite and continuously differentiable storage function $V(x)$ and non-negative weights $\{\epsilon, \varrho\}$ such that

$$\dot{V} = \left(\frac{\partial V}{\partial x}\right)^T f(x,u) \le u^T y + \frac{\epsilon}{2}\|u\|^2 - \frac{\varrho}{2}\|y\|^2. \tag{2}$$

The system (1) is said to have passivity-shortage or is said to be passivity-short as energy changes of the system are upper bounded by the weighted sum of power injected, input energy and output energy. On the other hand, energy changes of a passive system are upper bounded only by the input-output power injected. That is, if $\epsilon = 0$ in (2), mapping $\mathcal{P}$ is said to be *passive*. In addition, according to (2), system (1) is L_2 stable with and L_2 gain of $\frac{2\epsilon}{\varrho} + 4\varrho^2$.

Passivity-shortage and passivity have different implications for system stability. Previous studies have identified certain properties of the passivity-short systems that are distinctly different from that of passive systems with respect to stability and delay. The following properties summarize the results from these studies:

- **P1** System (1) is L_2 stable, if $V(x)$ is positive definite and $\varrho > 0$ [32], [33].
- **P2** When $\varrho = 0$, system (1) can recover its L_2 stability using a negative feedback control $u(t) = v - \frac{y(t)}{\epsilon}$ for the input output pair, $\{v, y\}$ [33].
- **P3** If system (1) is L_2-stable passivity-short and zero-state observable, then according to the Lyapunov direct method, (1) is asymptotically stable at the origin [33].
- **P4** Nyquist plot of a passive system lies completely on the left half of the s-plane, but an L_2 stable passivity-short system is not limited to the left half of the s-plane. It can lie slightly on the right half plane.
- **P5** Negative feedback interconnection of two passivity-short L_2 stable systems are also passivity-short and L_2 stable, under certain gain conditions [27].

In the subsequent discussion, the passivity-short and L_2-stability properties are established for robotic dynamics in general. Consider the n-link dynamics for the ith robot:

$$M_i(x_i)\ddot{x}_i + C_i(x_i,\dot{x}_i)\dot{x}_i + g_i(x_i) = \tau_i, \tag{3}$$

where x_i, $\dot{x}_i$, $\ddot{x}_i$ are joint displacement, velocity and acceleration, respectively; $M_i(x_i)$ is the inertia matrix, $C_i(x_i,\dot{x}_i) \le \xi_{c_i}(x_i)\|\dot{x}_i\|$ is the Coriolis matrix, $\xi_{c_i}(x_i)$ is either a known constant if the arm is all-revolute-joint or a known function if the arm has prismatic joint(s), $g_i(x_i)$ is the gravity vector, and τ_i is the torque control input chosen as

$$\tau_i = v_i + g_i(x_i) - k_{p_i}x_i - k_{v_i}\dot{x}_i, \tag{4}$$

which is a simple PD feedback control, with gravity compensation, and v_i is the overall system input (for force or torque). And, the corresponding Lyapunov function is given by

$$\begin{aligned} V_i &= \begin{bmatrix} x_i^T & \dot{x}_i^T \end{bmatrix} \begin{bmatrix} \alpha_i I & \sigma_i M_i \\ \sigma_i M_i & M_i \end{bmatrix} \begin{bmatrix} x_i \\ \dot{x}_i \end{bmatrix} \\ &= \alpha_i x_i^T x_i + \dot{x}_i^T M_i(x_i)\dot{x}_i + 2\sigma_i \dot{x}_i^T M_i(x_i) x_i, \end{aligned} \tag{5}$$

where $\alpha_i > 0$ is a constant, σ_i is a positive constant satisfying $\sigma_i^2 \leq \alpha_i \lambda_{\min}(M_i)/\lambda_{\max}^2(M_i)$. It is straightforward to verify that, under the choices of α_i and σ_i, Lyapunov function (5) is positive definite. Based on standard properties of robotic dynamics summarized in [34], it is shown in [15] that the robot dynamics in (3) is passivity-short and L_2 stable from input v_i to position output x_i, with passivity-short indices $[\varrho_i, \epsilon_i] = [k_{p_i}, 1/(2\alpha_i - \lambda_{\max}(M_i))]$ in (2).

Remark 1: Passivity holds only from v_i to velocity output $\dot{x}_i$. One of the existing approaches in the literature to address the loss of passivity is to introduce an input feedforward. Still, passivity is only for the augmented output, and the real system output suffers from degraded performance. In comparison, the proposed method establishes passivity-short and L_2-stable properties for the physical output.

Also, it has been proven in [15] that properties of passivity-short systems are retained in different configurations, and teleoperation in the presence of constant time delays, and it is extended to the varying-delay case in this letter. Teleoperation is a negative feedback configuration of robotic systems with delayed communication channels, as shown in Fig. 1. In a force-position based teleoperation cycle, the following steps take place: the master system receives an operator force F_h; the slave system receives a delayed version of the transmitted signal from the master (torque τ_m); the slave system which is subjected to an environmental force (F_e), sends its feedback (x_s) back to the master. Since passivity is a special case of passivity-short systems, the master/slave systems can be passive (if the output/input is velocity) or passivity-short. The master robot sends its state as well as the received slave state back to the operator. The communication channels back and forth may have different delays, which may vary with respect to time, which is the main issue that the proposed feedback control design should tackle.

The control design problem is to synthesize both master and slave controllers to meet the following objectives:

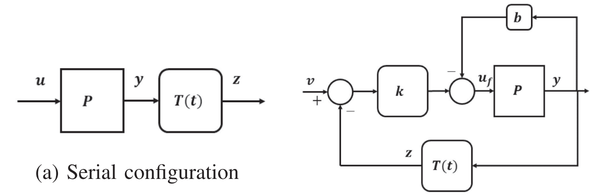
i) For any finite time-varying delays incurred in the communication channels, the overall system is to be input-to-state stable (with respect to operator input F_h).
ii) If the communication channels are interrupted, the system remains to be stable.
iii) Since the operator has direct control of the master device and wishes to control the slave (through delayed channels), the proposed controls are to minimize the lag and errors between the master output and slave output.
iv) The overall system remains L_2 stable, even when the environment is not stable.

III. Effects of Varying Time Delay

In this section, time-varying delayed interconnections of passivity-short systems are investigated in serial and feedback configurations. It is shown that passivity-short systems arise naturally from these configurations. The conditions for parameter selection are presented, which would eliminate the potentially destabilizing effect of varying time delays and preserve passivity-shortness and, in turn, the stability of the overall system.

A. Serial Connection

Consider a serial interconnection of dynamic mapping $\mathcal{P}$ of input-output pair $\{u, y\}$ and a time-varying delay channel whose output is $z(t) = y(t - T(t))$, as shown in Fig. 2(a). There are the following three cases of delayed signal $z(t)$ with different rates of change $\dot{T}$:



(a) Serial configuration

(b) Feedback configuration

Fig. 2. Interconnection of a passivity-short system and a time-varying delay.

- If $\dot{T} < 1$, $z(t)$ remains to be a delayed version of signal $y(t)$, and the resulting system depicted in Fig. 2(a) remains to be a causal dynamical system.
- Whenever $\dot{T} = 1$, $(t - T(t))$ becomes a constant and so does signal $z(t)$, in which case the resulting system is no longer a dynamical system.
- Should $\dot{T}(t) > 1$,

$$t + \delta t - T(t + \delta) = t - T(t) - (\dot{T} - 1)\delta t < t + T(t)$$

holds for any small $\delta t > 0$, and signal $z(t + \delta)$ would become a δt-time-reverse version of $y(\cdot)$, which makes the resulting system non-causal.

Hence, we have the following property for the purpose of investigating control design and stability of dynamical systems.

Property A: The delayed system depicted in Fig. 2(a) is a causal dynamical system, that is, $\dot{T}(t) < 1$ for all t.

It is worth noting that the continuous-domain condition of $\dot{T} \leq 1$ has been used in the literature, for example, [35]. In the remainder of this letter, Property A is always used. The following lemma summarizes the stability properties, and its proof is included in the appendix.

Lemma 1: Consider passivity-short mapping $\mathcal{P}$ as defined in (2) and with weights $\{\epsilon, \varrho\}$. Suppose that there exist positive constants c_1, c_2 and ϱ' such that

$$\varrho \geq c_1 + \frac{1}{c_2}, \tag{6}$$

$$0 \leq \inf_t \left[\frac{c_1}{2}\left(1 - \dot{T}\right) - \frac{1}{2c_2} \right] \triangleq \varrho'. \tag{7}$$

Then, the dynamic mapping $\mathcal{P}'$ from u to z is also passivity-short with weights $\{\epsilon', \varrho'\}$, where $\epsilon' = \epsilon + 2c_2$ and ϱ' is defined by (7).

Note that, under Property A, inequality (7) and hence existence of $\varrho' > 0$ can be satisfied by simply choosing small c_1 and large c_2 and that inequality (6) is a requirement on the value of ϱ. Thus, L_2 stability of the serial connection in Fig. 2(a) is assured.

The expression of $\epsilon' = \epsilon + 2c_2$ has two implications. First, it illustrates the invariance of passivity-shortage under time delay. Second, a pure time delay is not passive (its Nyquist plot is a unit circle, refer property P4) and, as shown by lemma 1, a passive system (with $\epsilon = 0$) followed by a time delay is no longer passive but passivity-short (i.e., $\epsilon' > 0$). That is, a time delay or a delayed dynamic system is passivity-short by nature. This observation is one of the reasons to adopt the passivity-short framework in this letter to investigate the stability of teleoperation.

It is also worth noting that, if $\varrho = 0$, mapping $\mathcal{P}$ is passivity-short but not L_2-stable. In this case, inequality (6) cannot be satisfied, thus resulting in an additional positive term and consequently, loss of L_2 stability. Nonetheless, according to the property P2, the L_2 stability can be recovered by using a feedback control $u(t) = v - bz(t)$ with the new input-output pair $\{v, z\}$. That is, the value of ϱ can always be made to be sufficiently positive to ensure inequality (6).

B. Feedback Configurations

It is known that passivity is preserved in a delayed negative feedback interconnection. In this subsection, it is shown that the same property applies to a passivity-short system as well. Besides, it can also be shown that a varying-time delayed positive feedback interconnection of any system is also passivity-short, and L_2 stability can be achieved by a simple feedback interconnection. The following lemma summarizes the stability results, and its proof is analogous to that of Lemma 1, and due to space limitation, it is omitted.

Lemma 2: Consider passivity-short mapping $\mathcal{P}$ as defined in (2) with input-output pair $\{u_f, y\}$ and weights $\{\epsilon, \varrho\}$. Suppose that there exist positive constants c_1, c_2, k and b such that

$$0 \le \inf_t \left[\frac{\varrho + 2b}{2k} - \frac{c_2}{2} - \frac{b\epsilon_f + c_1}{2k} \right] \triangleq \varrho_f, \qquad (8)$$

$$0 < \epsilon_f < \left[\frac{c_1}{2k}\left(1 - \dot{T}\right) - \frac{1}{2c_2} \right], \qquad (9)$$

where

$$\epsilon_f = \epsilon\left(k + \frac{b}{2}\right). \qquad (10)$$

Then, the dynamic mapping $\mathcal{P}_f$ from v to y is also passivity-short with weights $\{\epsilon_f, \varrho_f\}$ defined by (10) and (8) respectively.

Lemma 2 has two conditions. The first condition (8) ensures the existence of $\varrho_f > 0$, thus L_2 stability of the overall system in Fig. 2(b), and the value for ϵ_f is given directly by equation (10). The second condition (9) on ϵ_f can always be made due to Property A, and it implies that the resulting system can be passivity-short but not passive.

The gains are chosen as follows: For given weights $\{\epsilon, \varrho\}$, a small positive value for c_1 is chosen such that the quadratic inequality $\frac{\epsilon b^2}{2} - 2b < \varrho - \frac{c_1}{2}$ can be solved for a positive b. Substituting the chosen values of c_1 and b in $\varrho \ge c_2 k + c_1$, and $k \in [0, \frac{1}{c_2 + \epsilon b}\{\varrho + 2b - \frac{\epsilon b^2}{2} - \frac{c_1}{2}\}]$, would yield two linear inequalities with two unknown variables c_2 and k, that is solved for a large positive c_2 and a small positive k. Small c_1 along with large c_2 and k ensures inequality (9), according to Property A. It is to be noted that the left-hand side of (9) is satisfied as $k > 0$ in (10) making $\epsilon_f > 0$.

Lemma 2 can also be applied to passivity-short mapping $\mathcal{P}$ with no L_2 stability ($\varrho = 0$). In this case, the L_2 stability of the negative feedback is achieved by choosing a local gain $b > 0$. On the other hand, if the mapping $\mathcal{P}$ is passive ($\epsilon = 0$), then the overall negative feedback is passive.

From Lemma 2, it is evident that if system $\mathcal{P}$ in Fig. 2(b) is passivity-short, then the overall system is passivity-short, and L_2 stability for this interconnection can always be achieved. If $\mathcal{P}$ is passive, then the overall system is passive. This property can be used to design a teleoperation controller that can include either passive or passivity-short master and slave systems.

In the following section, the above negative feedback configuration is extended to a multi-loop feedback configuration for the bilateral teleoperation shown in Fig. 1.

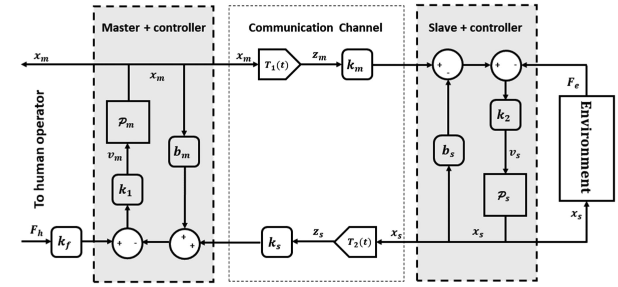


Fig. 3. Proposed passivity-shortage based framework.

IV. Main Results

In this section, stability analysis and performance conditions are discussed for a teleoperation configuration. The master and slave robots are considered to be passivity-short, with individual PD control and gravity compensation (as discussed in Section II) and the communication channel is assumed to have a time-varying delay. The slave robot is subjected to an environmental force, and the environment is considered to be passivity-short. It is shown that the overall system is passivity-short and L_2 stability is achieved under certain conditions.

Consider passivity-short mappings $\mathcal{P}_m$ with input v_m and output x_m, and $\mathcal{P}_s$ with input v_s and output x_s to represent the master and slave systems, with the rigid body dynamics (3), and for positive definite storage function (5), they are L_2 stable with parameters $[\varrho_m, \epsilon_m]$, $[\varrho_s, \epsilon_s]$ respectively.

The proposed bilateral teleoperation configuration, shown in Fig. 3, consists of three components: a master robot with its own feedback controller, a slave robot with its own feedback controller, and a closed loop of the master-slave pair with two varying communication delays. Both the master and slave controllers are of standard negative feedback type, and their control inputs v_m and v_s are expressed as:

$$v_m(t) = k_1\left(k_f F_h(t) - k_s z_s(t) - b_m x_m(t)\right), \qquad (11a)$$

$$v_s(t) = k_2\left(k_m z_m(t) - b_s x_s(t)\right) - F_e(t), \qquad (11b)$$

where b_m and b_s are individual feedback gain for the master and slave systems respectively; k_m and k_s are communication channel gains; and k_1 and k_2 are additional gains introduced to improve the performance characteristics, and k_f is the input scaling factor. The variables $z_m(t) = x_m(t - T_m(t))$ and $z_s(t) = x_s(t - T_s(t))$ denote the varying-time delayed outputs. The following theorem outlines the stability results of this system based on the passivity-short properties (which include passive systems as a special case), and the proof is included in the appendix.

Theorem 1: Consider passivity-short mappings $\mathcal{P}_m$, $\mathcal{P}_s$. The overall system in Fig. 3 with control input (11a) and (11b), is passivity-short and L_2 stable, from input $[F_h, F_e]$, to output

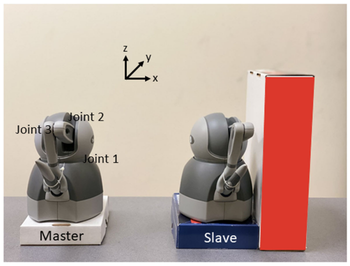


Fig. 4. Experimental Setup.

$[x_m, x_s]$, and new weights $\{\epsilon', \varrho'\}$, if the following two conditions are satisfied:

i) *Property A can be strengthened to be: for* $i = 1, 2$

$$\dot{T}_{i,\max} \triangleq \sup_t \dot{T}_i(t) < 1.$$

ii) *There exists positive gains and arbitrary constants* c_1, c_2 *and* c_3*, such that:*

$$0 \leq \inf_t \left[\frac{\varrho_m}{2} + k_1 b_m - \frac{3b_m^2 \epsilon_m k_1^2}{2} - \frac{c_1}{2} - c_m \right] \triangleq \varrho_m',$$

$$0 \leq \inf_t \left[\frac{\varrho_s}{2} + k_2 b_s - \frac{3b_s^2 \epsilon_s k_2^2}{2} - c_2 - \frac{c_s}{2} \right] \triangleq \varrho_s',$$

$$\epsilon_m' = \left[\frac{3}{2} \epsilon_m k_1 k_f \right], \qquad \epsilon_s' = \left[\frac{3}{2} \epsilon_s k_2^2 \right]. \tag{12}$$

Condition (i) is in essence the uniform version of Property A. As shown in the proof of the theorem, the weights c_m, c_s associated with the delay channel are chosen as:

$$c_m \geq \frac{1}{(1 - \dot{T}_{1,\max})} \left(3\epsilon_s k_2^2 k_m^2 + \frac{k_2^2 k_m^2}{c_2} \right),$$

$$c_s \geq \frac{1}{(1 - \dot{T}_{2,\max})} \left(3\epsilon_m k_1^2 k_s^2 + \frac{k_1^2 k_s^2}{c_1} \right), \tag{13}$$

which requires condition (i). To meet condition (ii) and in-turn achieve L_2 stability of the overall system, gains $k_m, k_s, b_m, b_s, k_1, k_2, k_f$ need to be picked such that inequalities from (12) to (13) are satisfied.

However, in addition to achieving stability, teleoperation needs improved performance such as minimum error between the output of the master and slave systems, and minimum phase lag. Such performance improvements are model-specific. This is achieved by ensuring a unity DC gain in the closed-loop transfer function between the master and slave subsystems, as discussed in [15]. The gains can be chosen using a simple iterative search under the above conditions.

It is also worth pointing out that Theorem 1 implies that the overall system is passivity-short but not passive because the gains k_1 and k_f are positive; hence ϵ_m' and ϵ_s' are positive.

V. Experiments

In this section, the experimental setup is outlined, and the comparative results are provided. The setup consists of two Geomagic Touch (previously Phantom Omni) haptic devices, as shown in Fig. 4. They have 3 DOF actuated joints and a 3 DOF stylus pen. In this experiment, only the first 3 joints are considered, and the stylus pen is immobilized. The two devices are connected to the same computer, and master/slave controllers are implemented in MATLAB/Simulink, using the Simulink library PhanSim [36]. Two sets of experiments are conducted: one in the environment where a "rigid" object in the form of a red box (as shown in Fig. 4) constrains the slave's first joint, and another in the free space (without any constraint).

The input from the human operator aims to move all the joints to their full ranges of motion. The communication channel is simulated with a variable-time delay, randomly generated under a normal distribution. Unless stated otherwise, the randomly varying time delay is generated with mean $0.6s$ and the maximum rate of change of delay, $\dot{T}_{\max} = 0.1$. Since the master and the slave devices have the same structure, their PD parameters set as $k_{pi} = 0.6$, $k_{vi} = 0.2$, for $i = m, s$. The maximum eigen value of the inertia matrix used in the experiment is $\lambda_{\max}(M_i) = 3.19 * 10^{-4}$ (same for both master and slave), obtained by a simple system identification of the haptic devices used. Hence, following (12), the control gains are chosen as $k_f = 1.6$, $k_m = 0.5$, $k_s = 0.55$, $k_1 = 1$, $k_2 = 1$, $b_m = 1.05$, $b_s = 0.5$.

A. Free-Space Motion

The results of the free-space experiments are shown in Fig. 5 in terms of joint position outputs of the master and slave systems, their joint torques, and the instantaneous position errors over time. It can be seen that the position and torque trajectories of the master and slave converge to each other, and hence stability is demonstrated. The position errors are due to the phase lag caused by the delay, which is inevitable, but at the steady-state, the position errors become convergent. Their torque response shows that the proposed method has a good force reflection. Their corresponding cartesian trajectories are shown in Fig. 6. It can be seen that in addition to velocity synchronization (which is used in all passivity-based teleoperation approaches in the literature and [17]), our proposed approach also ensures that position synchronization in the joint space renders position synchronization in the task space.

In addition to stability, there exists a measure of performance known as transparency, generally discussed in the force control literature [37]. In ideally transparent teleoperation, where the master and slave systems are defined by the same dynamics and Denavit-Hartenberg (DH) parameters, with delay-free communication, there exists a kinematic correspondence between the resulting master and slave position and force responses, throughout the teleoperation cycle. During such a correspondence, the impedance perceived by the human operator matches the environment impedance. Transparency of teleoperation can also be measured by the transparency index (μ), which is the ratio of percentage amplitude error (PAE) between the master and slave position responses, and PAE between their torque responses. Such an index of an ideal transparent system would be $\mu_{ideal} = 1$. Given the objective of this research on robust stability and convergence, and with the master and slave systems defined by the same dynamics and DH parameters, the measures of phase lag and PAE are used as performance indices in this letter. The PAE and phase lag between the master and slave position response for the three joints are $[0.65425, -0.0053]$, [2.55,0], and [0.99,0], and between their torque responses are $[0.7921, -0.0620]$, [3.110,0], and [3.78,0], respectively. The average transparency index of this teleoperation cycle is

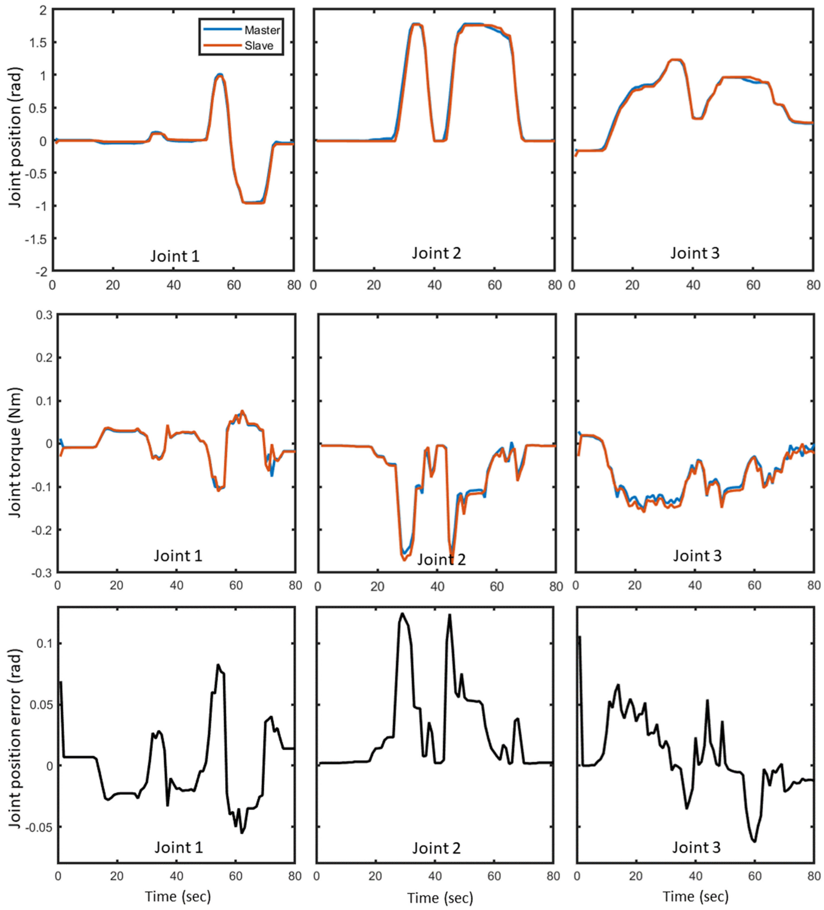


Fig. 5. Joint position (top), torque (mid) and position error (bottom) of the proposed approach in free space.

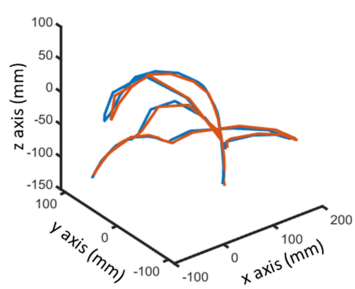


Fig. 6. Cartesian trajectories under the proposed approach in free space.

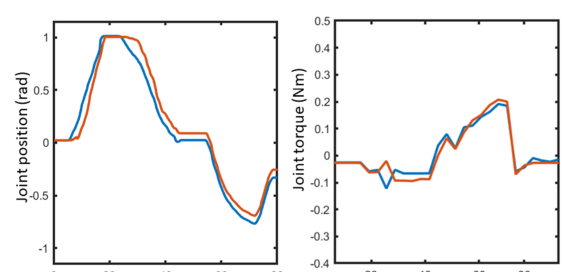


Fig. 7. Joint position and torque for the proposed approach in free space with large slow-varying delays.

$\mu_{avg} = 0.6323$, and a phase lag closer to zero indicates that the slave responds very fast to the master system.

The proposed approach is also applied to teleoperation with larger communication delays. Since the performances on different joints are similar, only the results of the first joints of the master and slave are presented here in this paragraph. Performance of the proposed approach in the presence of higher varying-delays (of a mean 5s and maximum rate of change $\dot{T}_{\max} = 0.1$) is shown in Fig. 7, where the position and torque trajectories of the slave track those of the master, with the same amplitudes but with a higher phase lag. The PAE and phase lag of this position and torque responses are $[2.432, -0.1850]$, $[4.0392, -0.1581]$, $\mu_{avg} = 0.6021$. Higher phase lag is expected due to a larger delay, but it is evident that the transparency is not affected due to the large delay.

B. Motion in Constrained Environment

The experiment is also conducted in a “rigid” environment where a hard constraint is placed on the first joint (by the red box in Fig. 4). The position and torque output are shown in Fig. 8. It can be seen that the environment constrains the movement of the slave system (position trajectory) from 50 s to 65 s and, during that period, the torque is increased on the slave side. This contact torque is also felt on the master side, even though the operator tries to keep moving along the desired trajectory, and

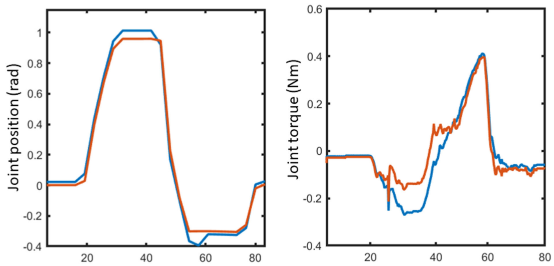


Fig. 8. Joint position and torque output of the proposed approach in a "rigid" environemnt.

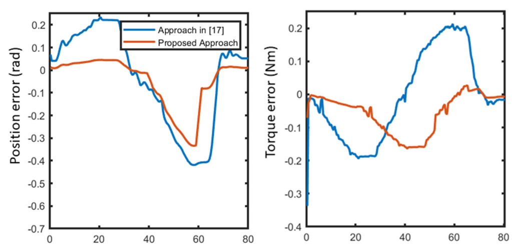


Fig. 9. Comparision between the proposed approach and [17].

this force feedback increasingly forces the master position back to that corresponding to the slave position.

C. Comparative Study

To further demonstrate the effectiveness of the proposed approach, a comparative study against [17] is presented. The technique proposed in [17] is an integral quadratic constraint (IQC) framework that uses a Zames-Falb multiplier to model delays and the environment of two-channel teleoperation. The overall system is transformed into a negative feedback interconnection of two blocks: a linear system block and the uncertainties block. Then, a multiplier is searched such that the uncertainties satisfy the IQC. Even though this approach allows the uncertainties block to accommodate the loss of passivity in master or slave systems, the formulated constraints require strict passivity. As a result, the overall system is subjected to passivity conditions. The result of this approach is shown in comparison to the proposed in Fig. 9, which compares the master and slave joint position errors and torque errors. As used in [17], the gains are chosen as $\mu = 0.8$, and $K_f = 0.6$. The proposed method is far more effective than IQC, in the sense of smaller errors. Besides, it can be seen that the position error during contact with the rigid body (between 50s and 65s) is lesser for the proposed approach, and it is also more responsive to the environmental disturbances.

VI. Conclusion

In this letter, a new multi-loop feedback control configuration is proposed for bilateral teleoperation. The proposed control design framework uses the concept of passivity-shortage and hence, can make a much wider class of dynamic systems admissible for teleoperation. Included in the proposed design are two separate, local negative feedback loops for the master and slave systems, respectively, so both become L_2 stable. Then, a larger feedback loop is closed to include the master system, the slave system, and the communication channels between them. Analytical design criteria are found for choosing control gains so that the stability of the overall system is ensured for all delays that may be time-varying. Experiments are carried out to demonstrate that the proposed control enables fast-responding and stable teleoperation for manipulators that are potentially of high-order and high-relative degree dynamics, even in the presence of time delay and stiff environment.

Appendix

A. Proof of Lemma 1

It follows from Fig. 2(a) that $z(t) = y(t - T(t))$. Choose the storage function of the overall system as

$$L = V + V_d, \tag{14}$$

where V is the storage function of mapping $\mathcal{P}$ and V_d is the storage function associated with delay for positive constant c_1 is

$$V_d(t, T(t)) = \frac{c_1}{2} \int_{t-T(t)}^{t} \|y(\tau)\|^2 d\tau. \tag{15}$$

Then, it follows from (3) that

$$\begin{aligned}
\dot{L} \leq\ & u^T(t)y(t) + \frac{\epsilon}{2}\|u(t)\|^2 - \frac{\varrho}{2}\|y(t)\|^2 + \dot{V}_d \\
\leq\ & u^T(t)y(t) + \frac{\epsilon}{2}\|u(t)\|^2 - \frac{\varrho}{2}\|y(t)\|^2 + \frac{c_1}{2}\|y(t)\|^2 \\
& - \frac{c_1}{2}\left(1 - \frac{dT}{dt}\right)\|z(t)\|^2 \qquad (16) \\
\leq\ & u^T(t)z(t) + \left[\frac{\epsilon}{2} + c_2\right]\|u(t)\|^2 - \left[\frac{\varrho}{2} - \frac{c_1}{2}\right. \\
& \left. - \frac{1}{2c_2}\right]\|y(t)\|^2 - \left[\frac{c_1}{2}\left(1 - \frac{dT}{dt}\right) - \frac{1}{2c_2}\right]\|z(t)\|^2 \\
\leq\ & u^T(t)z(t) + \frac{\epsilon'}{2}\|u(t)\|^2 - \frac{\varrho'}{2}\|z(t)\|^2, \qquad (17)
\end{aligned}$$

where c_2 is any positive constant. This together with (6) completes the proof.

B. Proof of Theorem 1:

Consider the following storage function L_t:

$$L_t = \frac{1}{k_1 k_f} V_m(t) + V_s(t) + V_{d_m}(t, T_1) + V_{d_s}(t, T_2),$$

where $V_m(t)$ and $V_s(t)$ are the storage functions in the form of (5) (i.e., by replacing subscript $_i$ by $_m$ or $_s$), and $V_{d_m}(t, T_1)$ and $V_{d_s}(t, T_2)$ are delay channel storage functions in the form of (15), with associated positive constants c_m and c_s. Then, the time derivative of L_t becomes

$$\begin{aligned}
\dot{L}_t \leq\ & \frac{1}{k_1 k_f}\left[v_m^T(t)x_m(t) + \frac{\epsilon_m}{2}\|v_m(t)\|^2 - \frac{\varrho_m}{2}\|x_m(t)\|^2\right] \\
& + v_s^T(t)x_s(t) + \frac{\epsilon_s}{2}\|v_s(t)\|^2 - \frac{\varrho_s}{2}\|x_s(t)\|^2 \\
& + \frac{c_m}{2}\left[\|x_m(t)\|^2 - \|z_m(t)\|^2(1 - \dot{T}_1)\right] \\
& + \frac{c_s}{2}\left[\|x_s(t)\|^2 - \|z_s(t)\|^2(1 - \dot{T}_2)\right].
\end{aligned}$$

Substituting the proposed controllers in (11a) and (11b) into the above yields

$$\begin{aligned}\dot{L}_t \leq\ & F_h^T x_m + F_e^T x_s + \frac{3\epsilon_m k_1 k_f}{2}\|F_h\|^2 + \frac{3\epsilon_s k_2^2}{2}\|F_e\|^2 \\ & - \left[\frac{\varrho_m}{2} + k_1 b_m - \frac{3b_m^2 \epsilon_m k_1^2}{2} - c_1 - c_s\right]\frac{\|x_m\|^2}{k_f k_1} \\ & - \left[\frac{\varrho_s - \varrho_e}{2} + k_2 b_s - \frac{3b_s^2 \epsilon_s k_2^2}{2} - c_2 - c_m\right]\|x_s\|^2 \\ & - \left[\frac{c_m}{2}(1 - \dot{T}_{1,\max}) - \frac{k_2^2 k_m^2}{c_2} + \frac{3}{2}\epsilon_s k_2^2 k_m^2\right]\|z_m\|^2 \\ & - \left[\frac{c_s}{2k_f k_1}(1 - \dot{T}_{2,\max}) - \frac{3}{2k_f}\epsilon_m k_1 k_s^2 + \frac{k_1 k_s^2}{c_1 k_f}\right]\|z_s\|^2.\end{aligned}$$

It follows from passivity-shortage parameters ϵ_m, ϵ_s and ϱ_m, ϱ_s in (12) and from delay channel parameters in (13) that passivity-shortage is established as

$$\dot{L}_t \leq\ u^T y + \frac{\epsilon'}{2}\|u\|^2 - \frac{\varrho'}{2}\|y\|^2,$$

where $u = [F_h, F_e]$ and $y = [x_m, x_s]$. Positive values of the parameters $\epsilon' = [\epsilon'_m, \epsilon'_s]$, $\varrho' = [\varrho'_m, \varrho'_s]$ are ensured by (12). Thus, passivity-shortage and L_2 stability of the overall system is proved.

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