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Brief paper

Synchronization of bilateral teleoperators with time delay[☆]

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Abstract

Bilateral teleoperators, designed within the passivity framework using concepts of scattering and two-port network theory, provide robust stability against constant delay in the network and velocity tracking, but cannot guarantee position tracking in general. In this paper we fundamentally extend the passivity-based architecture to guarantee state synchronization of master/slave robots in free motion independent of the constant delay and without using the scattering transformation. We propose a novel adaptive coordination architecture which uses state feedback to define a new passive output for the master and slave robots containing both position and velocity information. A passive coordination control is then developed which uses the new outputs to state synchronize the master and slave robots in free motion. The proposed algorithm also guarantees ultimate boundedness of the master/slave trajectories on contact with a passive environment. Experimental results are also presented to verify the efficacy of the proposed algorithms.

Keywords: Bilateral teleoperation; Passivity-based control; Networks; Time delay; Adaptive control

1. Introduction

In this paper we address the problem of bilateral teleoperation that has widespread applications in areas such as operations in hazardous environments, undersea exploration, robotic surgery, drilling, etc. We refer the reader to Hokayem and Spong (2006) for a detailed survey of the various schemes developed for the problem of bilateral teleoperation and their stability analysis. Henceforth, we restrict ourselves to the discussion of passivity-based methods in bilateral teleoperation.

The passivity-based approach developed in Anderson and Spong (1989) and Niemeyer and Slotine (1991) has been the cornerstone of teleoperator control for the last two decades. Subsequent schemes, building upon the above two approaches, have been suggested in Chopra, Spong, Hirche, and Buss (2003), Chopra, Spong, and Lozano (2004), Chopra, Spong, Ortega, and Barabanov (2006), Kosuge, Murayama, and Takeo (1996), Lee and Spong (2006), Lozano, Chopra, and Spong (2002), Munir and Book (2002), Niemeyer and Slotine (1991), Ryu, Kwon, and Hannaford (2004), Stramigioli, Schaft, Maschke, and Melchiorri (2002) and Tanner and Niemeyer (2005) among others, to provide performance improvement via position feedback, impedance matching, robustness to time-varying delays and various other objectives.

However, most passivity-based architectures, notable exceptions being Chopra et al. (2006), Lee and Spong (2006) and Niemeyer and Slotine (1997), dictate transfer of velocity information between the master and the slave. Consequently, mismatch of initial conditions can result in position drift between the master and the slave robots. Therefore, development of a stable high performance bilateral teleoperator necessitates transmission of position information between the master and the slave robot. This was considered in Chopra et al. (2006) and Lee and Spong (2006), where the coupling gains were delay dependent, and in Niemeyer and Slotine (1997)

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where position information was encoded by transmitting the integral of the wave-variables (Niemeyer & Slotine, 1991). Synchronization-based approaches for robot control have been developed in Chopra and Spong (2006, 2005) and Rodriguez-Angeles and Nijmeijer (2004) and the application of synchronization to bilateral teleoperation has been demonstrated in Chopra and Spong (2005).

In this paper we view the problem of bilateral teleoperation from the perspective of state synchronization. The performance goals are:

G1: Demonstrate ultimate boundedness of master/slave trajectories, in both free and constrained motions, independent of the constant time delay.

G2: Synchronize the positions of the master and the slave robot when the slave is allowed to move freely.

G3: Ensure boundedness of the force tracking error between the human-operator force and the environmental force experienced by slave on hard contact with the environment.

Our contributions in this paper are as follows:

- In Section 2.1 we propose an adaptive feedback control law for the master and the slave manipulator that renders the manipulator dynamics passive with respect to an output that contains both position and velocity information.
- We develop a passive coordination control law that state synchronizes the master and slave robots in free motion, independent of the constant delay.
- In Section 2.2 we demonstrate ultimate boundedness of all signals on hard contact for a class of non-passive human-operator models and passive environment models. In addition, if there is no communication delay, we obtain sharp asymptotic estimates for the states of the master and slave robots.
- Experimental results, using two direct-drive, planar, two-degree-of-freedom robots, are presented in Section 3.

2. Synchronization architecture for bilateral manipulators

Neglecting friction or other disturbances, the Euler–Lagrange equations of motion for an n-link master and slave robot are given as (Spong, Hutchinson, & Vidyasagar, 2006)

$$\begin{aligned} M_m(q_m)\ddot{q}_m + C_m(q_m,\dot{q}_m)\dot{q}_m + g_m(q_m) &= F_h(t) + \tau_m(t) \\ M_s(q_s)\ddot{q}_s + C_s(q_s,\dot{q}_s)\dot{q}_s + g_s(q_s) &= \tau_s(t) - F_e(t) \end{aligned} \tag{1}$$

where $q_m(t), q_s(t) \in R^{n\times 1}$ are the vectors of joint displacements, $\dot{q}_m(t), \dot{q}_s(t) \in R^{n\times 1}$ are the vectors of joint velocities, $\tau_m(t), \tau_s(t) \in R^{n\times 1}$ are the vectors of applied torques, $M_m(q_m), M_s(q_s) \in R^{n\times n}$ are the positive definite inertia matrices, $C_m(q_m,\dot{q}_m), C_s(q_s,\dot{q}_s) \in R^{n\times n}$ are the matrices of Centripetal and Coriolis torques and $g_m(q_m), g_s(q_s) \in R^{n\times 1}$ are the gravitational torques. The above equations exhibit certain fundamental properties due to their Lagrangian dynamic structure (Spong et al., 2006).

Property 1. *The inertia matrix $M(q)$ is symmetric positive definite and there exists a positive constant m such that*

$$mI \le M(q).$$

Property 2. *The Lagrangian dynamics are linearly parameterizable which gives us that*

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = Y(q,\dot{q},\ddot{q})\theta = \tau(t)$$

where θ is a constant p-dimensional vector of inertia parameters (such as link masses, moments of inertia etc.) and $Y(q,\dot{q},\ddot{q}) \in R^{n\times p}$ is the matrix of known functions of the generalized coordinates and their higher derivatives.

Property 3. *Under an appropriate definition of the matrix $C(q,\dot{q})$, the matrix $\dot{M}(q)$-$2C(q,\dot{q})$ is skew-symmetric.*

2.1. The free motion strategy

We first study the case of free motion, and assume that the human-operator force $F_h(t)$ and the environmental force $F_e(t)$ are zero. In free motion, and supposing that the forward and backward communication delays are equal, the bilateral teleoperator is said to state synchronize if

$$\begin{aligned} \lim_{t\to\infty} \|q_m(t-T) - q_s(t)\| &= \lim_{t\to\infty} \|\dot{q}_m(t-T) - \dot{q}_s(t)\| = 0 \\ \lim_{t\to\infty} \|q_s(t-T) - q_m(t)\| &= \lim_{t\to\infty} \|\dot{q}_s(t-T) - \dot{q}_m(t)\| = 0 \end{aligned} \tag{2}$$

where $\|\cdot\|$ denotes the Euclidean norm of the enclosed signal. It is important to point out that the equal forward/backward delay assumption has been made for the sake of simplicity and the subsequent results are valid even when the forward and backward delays are not equal.

In order to achieve the first design objective $G1$, we choose the master and slave inputs as

$$\begin{aligned} \tau_m(t) &= \bar{\tau}_m(t) - \hat{M}_m(q_m)\lambda\dot{q}_m(t) - \hat{C}_m(q_m,\dot{q}_m)\lambda q_m(t) \\ &\quad + \hat{g}_m(q_m) \end{aligned}$$

$$\tau_s(t) = \bar{\tau}_s(t) - \hat{M}_s(q_s)\lambda\dot{q}_s(t) - \hat{C}_s(q_s,\dot{q}_s)\lambda q_s(t) + \hat{g}_s(q_s) \tag{3}$$

where $\hat{M}_i(q_i)$, $\hat{C}_i(q_i,\dot{q}_i)$, $\hat{g}_i(q_i)$, $i = m, s$ are the estimates of the respective matrices available at that instant, λ is a constant positive definite matrix, and $\bar{\tau}_m(t)$, $\bar{\tau}_s(t)$ are the coordinating torques that will be described below.

As the dynamics are linearly parameterizable (Property 2), the motor torques can also be written as $\tau_m(t) = \bar{\tau}_m(t) - Y_m(q_m,\dot{q}_m)\hat{\theta}_m$; $\tau_s(t) = \bar{\tau}_s(t) - Y_s(q_s,\dot{q}_s)\hat{\theta}_s$, where $Y_m(q_m,\dot{q}_m)$, $Y_s(q_s,\dot{q}_s)$ are known functions of the generalized coordinates, and $\hat{\theta}_m(t)$, $\hat{\theta}_s(t)$ are the time-varying estimates of the manipulators' actual constant p-dimensional inertial parameters given by θ_m, θ_s respectively. Substituting (3) into (1), the master and slave dynamics (1) reduce to

$$\dot{q}_m(t) = -\lambda q_m(t) + r_m(t)$$

$$\begin{aligned} M_m(q_m)\dot{r}_m(t) + C_m(q_m,r_m)r_m(t) &= Y_m(q_m,r_m)\tilde{\theta}_m(t) \\ &\quad + \bar{\tau}_m(t) \end{aligned}$$

$$\dot{q}_s(t) = -\lambda q_s(t) + r_s(t)$$
$$M_s(q_s)\dot{r}_s(t) + C_s(q_s, r_s)r_s(t) = Y_s(q_s, r_s)\tilde{\theta}_s(t) + \bar{\tau}_s(t) \tag{4}$$

where $r_i(t) = \dot{q}_i(t) + \lambda q_i(t)$, $i = m, s$ are the new outputs of the master and slave robots respectively, and $\tilde{\theta}_m(t) = \theta_m - \hat{\theta}_m(t)$, $\tilde{\theta}_s(t) = \theta_s - \hat{\theta}_s(t)$ are the estimation errors.

Let the time-varying estimates of the uncertain parameters evolve as

$$\dot{\hat{\theta}}_m(t) = \Gamma Y_m^T(q_m, r_m)r_m(t); \qquad \dot{\hat{\theta}}_s(t) = \Lambda Y_s^T(q_s, r_s)r_s(t) \tag{5}$$

where Γ and Λ are constant positive definite matrices. To state synchronize the master and slave robots, the coordinating torques are given as

$$\bar{\tau}_s(t) = K(r_m(t-T) - r_s(t))$$
$$\bar{\tau}_m(t) = K(r_s(t-T) - r_m(t)) \tag{6}$$

where $K > 0$ is a constant. Define the coordination errors between the master and slave robots as

$$e_m(t) = q_m(t-T) - q_s(t); \qquad e_s(t) = q_s(t-T) - q_m(t). \tag{7}$$

Therefore, from (2), the master/slave robots state synchronize if the coordination errors and their derivatives approach the origin asymptotically.

It is to be noted (see Spong, Ortega, and Kelly (1990)) that $\bar{x}(t) = [q_m(t)\ q_s(t)\ \dot{q}_m(t)\ \dot{q}_s(t)\ \tilde{\theta}_m(t)\ \tilde{\theta}_s(t)]^T$ is related to the vector $x(t) = [q_m(t)\ q_s(t)\ r_m(t)\ r_s(t)\ \tilde{\theta}_m(t)\ \tilde{\theta}_s(t)]^T$ by a linear diffeomorphism, $\bar{x}(t) = Jx(t)$, where $J \in R^{6\times 6}$ is a nonsingular matrix. Hence, boundedness of $\bar{x}(t)$ implies that of $x(t)$ and vice versa. Denote by $\mathcal{C} = \mathcal{C}([-T, 0], R^n)$, the Banach space of continuous functions mapping the interval $[-T, 0]$ into R^n, with the topology of uniform convergence. Define $x_t = x(t+\phi) \in \mathcal{C}, -T \le \phi \le 0$ as the state of the system (Hale & Verduyn, 1993). We assume in this note that $x(\phi) = \eta(\phi), \eta \in \mathcal{C}$ and that all signals belong to $\mathcal{L}_{2e}$, the extended $\mathcal{L}_2$ space.

Theorem 2.1. *Consider the nonlinear bilateral teleoperation system in free motion ($F_h(t) = F_e(t) = 0$) described by (4)–(6). Then for all initial conditions, all signals in the system are bounded and the master/slave robots state synchronize in the sense of (2).*

Proof. Define a positive semi-definite storage functional $V : \mathcal{C} \to R^+$ for the system as

$$\begin{aligned} V(x_t) = {} & (r_m^T(t)M_m(q_m)r_m(t) + r_s^T(t)M_s(q_s)r_s(t) \\ & + e_m^T(t)K_1e_m(t) + e_s^T(t)K_2e_s(t) + \tilde{\theta}_m^T(t)\Gamma^{-1}\tilde{\theta}_m(t) \\ & + \tilde{\theta}_s^T(t)\Lambda^{-1}\tilde{\theta}_s(t)) + K\int_{t-T}^{t}(r_m^T(s)r_m(s) \\ & + r_s^T(s)r_s(s))\mathrm{d}s \end{aligned}$$

where K_1, K_2 are positive definite matrices to be determined. The derivative of $V(x_t)$ along the trajectories of system (4) is given by

$$\begin{aligned} \dot{V}(x_t) = {} & 2r_m^T(-C_mr_m + Y_m\tilde{\theta}_m + \bar{\tau}_m) + r_m^T\dot{M}_mr_m \\ & + 2r_s^T(-C_sr_s + Y_s\tilde{\theta}_s + \bar{\tau}_s) + r_s^T\dot{M}_sr_s + 2(\dot{e}_m^TK_1e_m \\ & + \dot{e}_s^TK_2e_s - \tilde{\theta}_m^TY_m^Tr_m - \tilde{\theta}_m^TY_s^Tr_s) + K(r_m^Tr_m \\ & - r_m^T(t-T)r_m(t-T) + r_s^Tr_s \\ & - r_s^T(t-T)r_s(t-T)). \end{aligned}$$

Using (6) and the skew-symmetric property (Property 3), the derivative reduces to

$$\begin{aligned} \dot{V}(x_t) = {} & 2(\dot{e}_m^TK_1e_m + \dot{e}_s^TK_2e_s) - K((r_m(t-T) - r_s)^T \\ & \times (r_m(t-T) - r_s) - (r_s(t-T) - r_m)^T \\ & \times (r_s(t-T) - r_m)) \\ = {} & 2\dot{e}_m^TK_1e_m - K(\dot{e}_m + \lambda e_m)^T(\dot{e}_m + \lambda e_m) \\ & + 2\dot{e}_s^TK_2e_s - K(\dot{e}_s + \lambda e_s)^T(\dot{e}_s + \lambda e_s). \end{aligned}$$

Choosing $K_1 = K_2 = K\lambda$, we get

$$\begin{aligned} \dot{V}(x_t) = {} & -K(\dot{e}_s^T(t)\dot{e}_s(t) + e_s^T(t)\lambda^2e_s(t) + \dot{e}_m^T(t)\dot{e}_m(t) \\ & + e_m^T(t)\lambda^2e_m(t)) \le 0. \end{aligned} \tag{8}$$

As $V(x_t)$ is positive semi-definite and $\dot{V}(x_t)$ is negative semi-definite, therefore $\lim_{t\to\infty} V(x_t)$ exists and is finite. Also, the signals $r_m(t), r_s(t), \tilde{\theta}_s(t), \tilde{\theta}_m, e_s(t), e_m(t) \in \mathcal{L}_\infty[0,\infty)$, and hence $\dot{e}_m(t), \dot{e}_s(t), \ddot{e}_m(t), \ddot{e}_s(t) \in \mathcal{L}_\infty[0,\infty)$. Integrating (8) and letting $t \to \infty$, it can be seen that $e_m(t)$, $e_s(t)$, $\dot{e}_m(t)$, $\dot{e}_s(t) \in \mathcal{L}_2[0,\infty)$. It is well known that a square integrable signal with a bounded derivative converges to the origin (Khalil, 2002). Thus, $\lim_{t\to\infty}\dot{e}_m(t) = \lim_{t\to\infty}\dot{e}_s(t) = \lim_{t\to\infty}e_s(t) = \lim_{t\to\infty}e_m(t) = 0$, consequently the master/slave robots state synchronize in the sense of (2). □

Remarks.
- Passivity of the master/slave robots with $r_m(t)$, $r_s(t)$ as outputs and $F_h(t), F_e(t)$ as inputs follows by using $V(x_t)$ as the storage functional.
- It seems likely that the passivity of the bilateral teleoperation system, in the presence of time-varying delays, can be established using the approach in Lozano et al. (2002).
- Theorem 2.1 can be easily extended to the case of asymmetric (constant) communication delays.
- The proposed approach is a specific application of the delay robustness property of passive systems with respect to linear coupling controls (Chopra & Spong, 2006).

It is interesting to relate the synchronizing control (6) to the scattering transformation-based coordination control law in Chopra et al. (2004). In Chopra et al. (2004), instead of transmitting the outputs $r_m(t), r_s(t)$ (4) directly, the outputs were encoded in the scattering transformation and the scattering variables were transmitted between the master and the slave robots. The coordination architecture proposed in Chopra et al. (2004) is shown in Fig. 1. The scattering (Anderson & Spong, 1989) or the wave-variables (Niemeyer & Slotine, 1991) are defined as

$$u_m(t) = \frac{F_{md}(t) + br_{md}(t)}{\sqrt{2b}}; \qquad v_m(t) = \frac{F_{md}(t) - br_{md}(t)}{\sqrt{2b}}$$

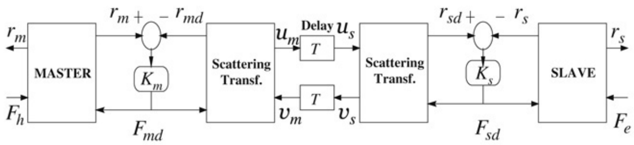

Fig. 1. The coordination architecture.

$$u_s(t) = \frac{F_{sd}(t) + br_{sd}(t)}{\sqrt{2b}}; \qquad v_s(t) = \frac{F_{sd}(t) - br_{sd}(t)}{\sqrt{2b}} \tag{9}$$

where $r_{sd}(t)$, $r_{md}(t)$ are the signals derived from the scattering transformation as shown in Fig. 1 and b, the characteristic wave impedance, is a positive constant. The torques $F_{sd}(t)$ and $F_{md}(t)$ were defined as

$$\bar{\tau}_s(t) = F_{sd}(t) = K_s(r_{sd}(t) - r_s(t)) \tag{10}$$

$$\bar{\tau}_m(t) = -F_{md}(t) = K_m(r_{md}(t) - r_m(t)) \tag{11}$$

where the gains K_s, K_m are positive constants.

If the network delay is constant, the transmission equations are given as

$$u_s(t) = u_m(t - T); \qquad v_m(t) = v_s(t - T).$$

Rewriting the first of the above equations using (9), we get

$$F_{md}(t - T) + br_{md}(t - T) = F_{sd}(t) + br_{sd}(t).$$

Substituting the coordination torques from (10) and (11), the transmission equation reduces to

$$\begin{aligned}
&K_m(r_m(t - T) - r_{md}(t - T)) + br_{md}(t - T)\\
&\quad = K_s(r_{sd}(t) - r_s(t)) + br_{sd}(t)\\
&\quad \Rightarrow (b - K_m)r_{md}(t - T) + K_m r_m(t - T)\\
&\quad = (K_s + b)r_{sd}(t) - K_s r_s(t)\\
&\quad \Rightarrow (b + K_s)r_{sd}(t) = (b - K_m)r_{md}(t - T)\\
&\qquad + K_m r_m(t - T) + K_s r_s(t).
\end{aligned} \tag{12}$$

Similarly, using the other transmission equation we have

$$\begin{aligned}
(b + K_m)r_{md}(t) = {}& (b - K_s)r_{sd}(t - T) + K_s r_s(t - T)\\
& + K_m r_m(t).
\end{aligned} \tag{13}$$

To avoids *wave reflections* (Niemeyer & Slotine, 1991; Stramigioli et al., 2002), the characteristic impedance is matched to the coupling gains by choosing

$$K_m = K_s = b$$

and the resulting transmission equations, free of the *wave reflections*, are given as

$$\begin{aligned}
2r_{sd}(t) &= r_m(t - T) + r_s(t)\\
2r_{md}(t) &= r_s(t - T) + r_m(t).
\end{aligned} \tag{14}$$

Substituting these transmission equations in the control laws (10), (11), we get

$$\begin{aligned}
\bar{\tau}_s(t) &= \frac{b}{2}(r_m(t - T) - r_s(t))\\
\bar{\tau}_m(t) &= \frac{b}{2}(r_s(t - T) - r_m(t)).
\end{aligned} \tag{15}$$

Choosing $K = \frac{b}{2}$ in (6), the above control law is equivalent to (6). Hence, the scattering transformation approach in Chopra et al. (2004) with impedance matching leads to the synchronizing control (6).

Our next claim addresses the case when the human operator is included in the control loop. We study the teleoperation problem when the human operator is modeled as a passive damper system, i.e. $F_h(t) = -K_h\dot{q}_m(t)$, $K_h > 0$. The system dynamics can now be written as

$$\begin{aligned}
&\dot{q}_m(t) = -\lambda q_m(t) + r_m(t)\\
&M_m(q_m)\dot{r}_m(t) + C_m(q_m, r_m)r_m(t) = Y_m(q_m, r_m)\tilde{\theta}_m(t)\\
&- K_h\dot{q}_m(t) + \bar{\tau}_m(t)\\
&\dot{q}_s(t) = -\lambda q_s(t) + r_s(t)\\
&M_s(q_s)\dot{r}_s(t) + C_s(q_s, r_s)r_s(t) = Y_s(q_s, r_s)\tilde{\theta}_s(t) + \bar{\tau}_s(t).
\end{aligned} \tag{16}$$

Theorem 2.2. *Consider the nonlinear bilateral teleoperation system described by (5), (6) and (16). Then for all initial conditions, all signals in the system are bounded, the master/slave robots state synchronize in the sense of (2) and the master/slave velocities converge to the origin.*

Proof. Consider a positive semi-definite storage functional $V : \mathcal{C} \to R^+$ for the system as

$$\begin{aligned}
V(x_t) = {}& (r_m^T(t)M_m(q_m)r_m(t) + r_s^T(t)M_s(q_s)r_s(t)\\
& + e_m^T(t)K_1e_m(t) + e_s^T(t)K_2e_s(t) + \tilde{\theta}_m^T(t)\Gamma^{-1}\tilde{\theta}_m(t)\\
& + \tilde{\theta}_s^T(t)\Lambda^{-1}\tilde{\theta}_s(t)) + K\int_{t-T}^{t}(r_m^T(s)r_m(s)\\
& + r_s^T(s)r_s(s))\mathrm{d}s + K_h q_m(t)^T\lambda q_m(t).
\end{aligned}$$

Following the proof of Theorem 2.1, and using that $F_h = -K_h\dot{q}_m(t)$, the derivative of $V(x_t)$ is given as

$$\begin{aligned}
\dot{V}(x_t) = {}& -K(\dot{e}_s^T(t)\dot{e}_s(t) + e_s^T(t)\lambda^2e_s(t) + \dot{e}_m^T(t)\dot{e}_m(t)\\
& + e_m^T(t)\lambda^2e_m(t)) - 2K_h\dot{q}_m^T(t)\dot{q}_m(t) \le 0.
\end{aligned}$$

As $\dot{V}(x_t)$ is negative semi-definite, therefore $\lim_{t\to\infty} V(x_t)$ exists and is finite. Following the proof of Theorem 2.1, it can be shown that all signals are bounded and $\lim_{t\to\infty}\dot{e}_m(t) = \lim_{t\to\infty}\dot{e}_s(t) = \lim_{t\to\infty}e_s(t) = \lim_{t\to\infty}e_m(t) = \lim_{t\to\infty}\dot{q}_m(t) = 0$ and the master/slave robots state synchronize. As $\dot{e}_m(t) = \dot{q}_m(t - T) - \dot{q}_s(t)$, the above limits imply that $\lim_{t\to\infty}\dot{q}_s(t) = 0$. □

Remark. • If the human operator provides a damping force, the above result demonstrates that in addition to state synchronization, the master/slave velocities converge to the origin, and the bilateral teleoperator reaches a steady state.

2.2. *The hard contact scenario*

In this section we study the stability (in the sense of the $\mathcal{L}_\infty[0, \infty)$ norm) of the bilateral teleoperator when the slave contacts a passive environment, and the human operator is modeled as a non-passive system. The human and the environment dynamics are given as

$$F_h(t) = \alpha_o - \alpha_m r_m(t); \qquad F_e(t) = \alpha_s r_s(t) \tag{17}$$

where $\alpha_o, \alpha_m, \alpha_s$ are bounded positive constants. This model encapsulates the scenario when the human-operator force tries to apply a constant non-passive force α_o, but is resisted by its passive dynamic component $-\alpha_m r_m(t)$. In the analysis that follows we assume that there is no uncertainty ($\tilde{\theta}_m, \tilde{\theta}_s \equiv 0$), in the inertial parameters of the master and slave robots. The system dynamics can be written as

$$\begin{aligned}
&\dot{q}_m(t) = -\lambda q_m(t) + r_m(t)\\
&M_m(q_m)\dot{r}_m(t) + C_m(q_m, r_m)r_m(t) = F_h(t) + \bar{\tau}_m(t)\\
&\dot{q}_s(t) = -\lambda q_s(t) + r_s(t)\\
&M_s(q_s)\dot{r}_s(t) + C_s(q_s, r_s)r_s(t) = \bar{\tau}_s(t) - F_e(t).
\end{aligned} \tag{18}$$

Then under the same assumptions as in Theorem 2.1, the following claim holds

Theorem 2.3. *Consider the nonlinear bilateral teleoperator described by (6), (17) and (18). In the presence of constant communication delays, all signals in the system are ultimately bounded.*

Proof. Consider a positive semi-definite storage functional $V : \mathcal{C} \to R^+$ for the system as

$$\begin{aligned}
V(x_t) &= r_m^T(t)M_m(q_m)r_m(t) + r_s^T(t)M_s(q_s)r_s(t)\\
&\quad + 2\alpha_m q_m^T(t)\lambda q_m(t) + 2\alpha_s q_s^T(t)\lambda q_s(t)\\
&\quad + K e_m^T(t)\lambda e_m(t) + K e_s^T(t)\lambda e_s(t)\\
&\quad + K\int_{t-T}^{t}(r_m^T(s)r_m(s) + r_s^T(s)r_s(s))\mathrm{d}s.
\end{aligned}$$

It is to be noted that $V(x_t) > 0,\ \forall x(t) \neq 0$. Differentiating $V(x_t)$ along trajectories of (18) we get

$$\begin{aligned}
\dot{V}(x_t) &= 2r_m^T(-C_m r_m + F_h + \bar{\tau}_m) + r_m^T\dot{M}_m r_m + 2r_s^T(-C_s r_s\\
&\quad + \bar{\tau}_s - F_e) + r_s^T\dot{M}_s r_s + 4(\alpha_m\dot{q}_m^T\lambda q_m + \alpha_s\dot{q}_s^T\lambda q_s)\\
&\quad + 2K(\dot{e}_m^T\lambda e_m + \dot{e}_s^T\lambda e_s) + Kr_m^T r_m - Kr_s(t-T)^T\\
&\quad \times r_s(t-T) + Kr_s^T r_s - Kr_m(t-T)^T r_m(t-T).
\end{aligned}$$

Using the values of $\bar{\tau}_m(t), \bar{\tau}_s(t)$ (6), the derivative reduces to

$$\begin{aligned}
\dot{V}(x_t) &= -K(r_s(t-T) - r_m)^T(r_s(t-T) - r_m)\\
&\quad - K(r_m(t-T) - r_s)^T(r_m(t-T) - r_s)\\
&\quad + 4(\alpha_m\dot{q}_m^T\lambda q_m + \alpha_s\dot{q}_s^T\lambda q_s)\\
&\quad + 2K(\dot{e}_m^T\lambda e_m + \dot{e}_s^T\lambda e_s) + 2(F_h^T r_m - F_e^T r_s)\\
&= -K(\dot{e}_s + \lambda e_s)^T(\dot{e}_s + \lambda e_s) - K(\dot{e}_m + \lambda e_m)^T\\
&\quad \times(\dot{e}_m + \lambda e_m) + 4(\alpha_m\dot{q}_m^T\lambda q_m + \alpha_s\dot{q}_s^T\lambda q_s)\\
&\quad + 2K(\dot{e}_m^T\lambda e_m + \dot{e}_s^T\lambda e_s) + 2(F_h^T r_m - F_e^T r_s).
\end{aligned}$$

Substituting the values of $F_h(t), F_e(t), r_m(t), r_s(t)$ (in terms of $q_i, \dot{q}_i, i = m, s$) and rearranging, $\dot{V}(x_t)$ can be rewritten as

$$\begin{aligned}
\dot{V}(x_t) &= -K(e_m^T\lambda^2 e_m + e_s^T\lambda^2 e_s) - K(\dot{e}_s^T\dot{e}_s + \dot{e}_m^T\dot{e}_m)\\
&\quad + 4(\alpha_m\dot{q}_m^T\lambda q_m + \alpha_s\dot{q}_s^T\lambda q_s) + 2((\alpha_o - \alpha_m r_m)^T\\
&\quad \times r_m - \alpha_s r_s^T r_s)\\
&= -K(e_m^T\lambda^2 e_m + e_s^T\lambda^2 e_s) - K(\dot{e}_s^T\dot{e}_s + \dot{e}_m^T\dot{e}_m)\\
&\quad - 2\alpha_m\dot{q}_m^T\dot{q}_m - 2\alpha_s\dot{q}_s^T\dot{q}_s - 2\alpha_m q_m^T\lambda^2 q_m\\
&\quad - 2\alpha_s q_s^T\lambda^2 q_s + 2\alpha_o(\dot{q}_m + \lambda q_m)\\
&\leq -K_{\min}\|\bar{x}\|^2 + 2\alpha_o\|\bar{x}\|\\
&\leq -K_{\min}(1-\beta)\|\bar{x}\|^2 - K_{\min}\beta\|\bar{x}\|^2 + 2\alpha_o\|\bar{x}\|
\end{aligned}$$

where $0 < \beta < 1$, $K_{\min} = \min(K\lambda_{\min}^2(\lambda), K, 2\alpha_m, 2\alpha_s, 2\alpha_m\lambda_{\min}^2(\lambda), 2\alpha_s\lambda_{\min}^2(\lambda))$, and $\lambda_{\min}(\cdot)$ is the smallest eigenvalue of the enclosed matrix. Recalling that $\bar{x}(t) = Jx(t)$,

$$\begin{aligned}
\dot{V}(x_t) &\leq -K_{\min}(1-\beta)\|\bar{x}(t)\|^2 \quad \forall\ \|\bar{x}(t)\| \geq \frac{2\alpha_o}{K_{\min}\beta}\\
&\leq -K_{\min}(1-\beta)\lambda_{\min}(J^T J)\|x(t)\|^2\\
&\qquad \forall\ \|x(t)\| \geq \frac{2\alpha_o}{\sqrt{\lambda_{\max}(J^T J)}K_{\min}\beta}.
\end{aligned}$$

As $K_{\min}, \beta$ are bounded away from zero, and α_o is assumed to be bounded, therefore for large values of the norm of $x(t)$, $\dot{V}(x_t) < 0,\ \forall x(t) \neq 0$. Consequently, the trajectories are ultimately bounded. □

We next obtain sharper asymptotic state estimates when there are no time delays in the network. In this scenario, the coordinating torques are given as $\bar{\tau}_m(t) = -\bar{\tau}_s(t) = K(r_s(t) - r_m(t))$, and the coordination error is defined as $e(t) = q_m(t) - q_s(t)$. Let the augmented state vector of the system be given as $x(t) = [q_m(t)\ q_s(t)\ \dot{q}_m(t)\ \dot{q}_s(t)\ e(t)]^T$. Under the same assumptions as in Theorem 2.1 we claim that

Theorem 2.4. *Consider the nonlinear bilateral teleoperator described by (17) and (18), and the aforementioned coordinating torques in the absence of communication delays. Then the nonlinear teleoperator is input-to-state stable (ISS) with respect to α_o.*

Proof. Consider a positive definite Lyapunov function $V : R^n \to R^+$ for the system as

$$\begin{aligned}
V(x) &= r_m(t)^T M_m(q_m)r_m(t) + r_s(t)^T M_s(q_s)r_s(t)\\
&\quad + 2\alpha_m q_m^T(t)\lambda q_m(t) + 2\alpha_s q_s^T(t)\lambda q_s(t)\\
&\quad + 2Ke^T(t)\lambda e(t).
\end{aligned} \tag{19}$$

Following the proof of Theorem 2.3, $\dot{V}(x)$ evaluated along trajectories of (18) satisfies

$$\dot{V}(x) \leq -K_{\min}(1-\beta)\|x(t)\|^2 \quad \forall\ \|x(t)\| \geq \frac{2\alpha_o}{K_{\min}\beta}$$

where $K_{\min} = \min(2K\lambda_{\min}^2(\lambda), 2K, 2\alpha_m, 2\alpha_s, 2\alpha_m\lambda_{\min}^2(\lambda), 2\alpha_s\lambda_{\min}^2(\lambda))$. As $V(x)$ is continuous, positive definite and radially unbounded, using Lemma 4.3 (Khalil, 2002) there exist class $\mathcal{K}_\infty$ functions α_1, α_2 functions such that

$$\alpha_1(\|x(t)\|) \leq V(x) \leq \alpha_2(\|x(t)\|).$$

Using Theorems 4.18, 4.19 (Khalil, 2002), the nonlinear teleoperator is ISS with respect α_o, and there exists $T > 0$, such that $\forall t \geq T$

$$\|x(t)\| \leq \alpha_1^{-1}\left(\alpha_2\left(\frac{2\alpha_o}{K_{\min}\beta}\right)\right). \quad \square$$

Theorems 2.3 and 2.4 demonstrate ultimate boundedness of the trajectories, and hence achieve goals $G1$ and $G3$. It is important to note that the results presented in this paper do not guarantee arbitrary switching between the free motion and the hard contact mode. However, it is reasonable to assume that dwell-time switching type arguments can be made to study the stability of the switched bilateral teleoperation system. We shall explore these questions in our future work.

3. Experiments

In this section, we test the proposed synchronization scheme under time-varying delays and packet losses. The experiments were performed on two direct-drive, planar, two-degree-of-freedom nonlinear robots exchanging information across a stochastic Internet model. Force sensors, located on the end-effectors, measure the force exerted by the operator/environment. The controllers and the Internet model were implemented using Wincon 3.3, which is a Windows application used for running real-time Simulink models. The reader is referred to Rodriguez-Seda, Lee, and Spong (2006) and Walsh (1994) for details on the manipulators and the stochastic Internet model respectively.

It is to be noted that adaptation was used both in free and constrained motion experiments. Observing the control law (5), it can be seen that the estimated parameters affect the transient performance of the bilateral teleoperator. Therefore, it would be judicious to confine the estimated parameters to lie in some compact set which also contains the unknown plant parameters θ_m and θ_s. This can be achieved by the well-known gradient projection method (Ioannou & Sun, 1996) which does not alter the properties of the original adaptation process (5).

In the experiments, time-varying delays between the master and the slave were fluctuating between (0.448, 0.544) s. The mean delay was 0.48 s with a standard deviation of 0.022 s. The human operator guided the second link of the master robot in the task space and the slave robot was coupled to the master robot using the proposed controller. The packet loss rate in the experiments ranged from 45% to 55%. In the free motion experiment, as seen in Fig. 2, the tracking performance is good in the face of time-varying delays and packet losses. The steady state errors were 0.0853 rad and 0.1125 rad for the first and second link respectively. The steady state errors may be attributed to the Coulomb friction present in the robots.

In the next experiment, the motion of the slave (the second link) is constrained by an aluminium wall, approximately during the $(8, 17)$ s of motion. The trajectories of the master/slave robots are shown in Fig. 3. The human-operator/environment forces at the end effectors, are plotted in Fig. 4, and thus the proposed algorithm provides reasonable force tracking on contact with the environment.

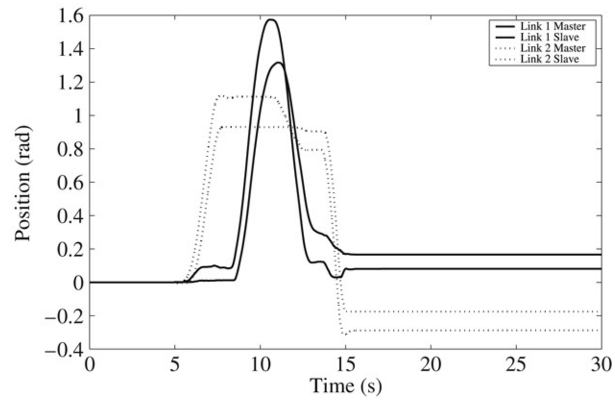

Fig. 2. Master and slave trajectories during free motion.

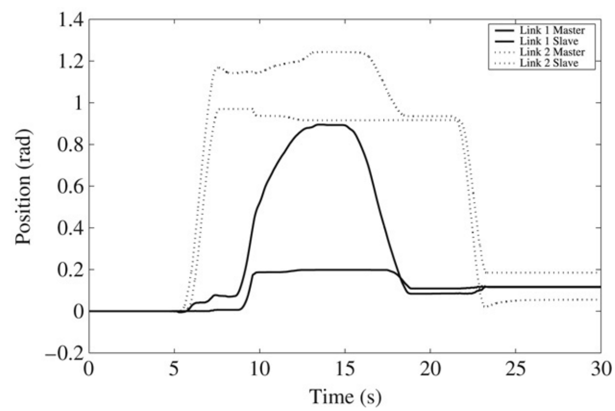

Fig. 3. Master and slave trajectories in the constrained motion experiment.

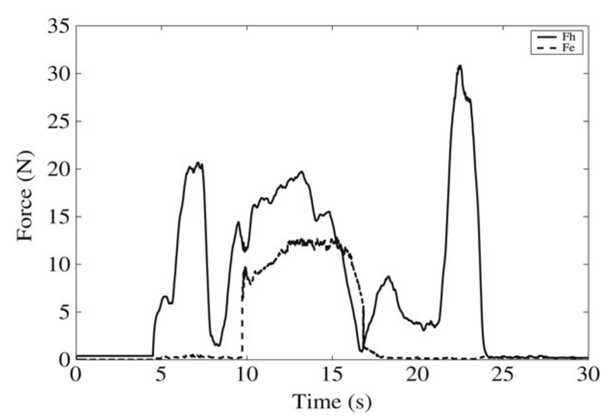

Fig. 4. Human-operator and environment forces in the constrained motion experiment.

4. Conclusions

In this paper algorithms for bilateral teleoperation were developed that guaranteed ultimate boundedness of master/slave trajectories, in both free and constrained motion, independent of the constant network delay and without using the scattering transformation. Adaptive coordination control laws were proposed which ensured state synchronization of the master/slave robots in free motion. On hard contact with the environment, ultimate boundedness of all signals was demonstrated for a non-passive human-operator model and passive environment model. Experimental results using planar, two-degree-of-freedom nonlinear robots, were also presented.

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