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STABILITY AND TRANSPARENCY OF DELAYED BILATERAL TELEOPERATION WITH HAPTIC FEEDBACK

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Haptic guidance can improve control accuracy in bilateral teleoperation. With haptic sensing, the human operator feels that he grabs the robot on the remote side. There are results on the stability and transparency analysis of teleoperation without haptic guidance, and the analysis of teleoperation with haptic feedback is only for linear and zero time-delay systems. In this paper, we consider more general cases: the bilateral teleoperation systems have time-varying communication delays, the whole systems are nonlinear, and they have force feedback. By using the admittance human operator model, we propose a new control scheme with the interaction passivity of the teleoperator. The stability and transparency of the master-slave system are proven with the Lyapunov–Krasovskii method. Numerical simulations illustrate the efficiency of the proposed control methods.

Keywords: teleoperation, force control, stability, transparency.

1. Introduction

Teleoperation systems have become an extensive and interesting field for researchers in the last decade, with the ability to operate from a remote location as the main function of teleoperation systems. It has widespread applications in many areas such as space mission, undersea exploration, hazardous environment, tele-surgery, etc. (Nohmi, 2003; Hokayem and Spong, 2006; Jordan and Bustamante, 2007; Kawashima *et al.*, 2008; Erden and Mari, 2011; Ehrampoosh *et al.*, 2013).

$$\mathbf{u}_i = \frac{1}{k_i} \sum_{j \in N_{i,k}} (x_j - x_i)$$

The teleoperation system is a two-port structure as shown in the Fig. 1. It is commonly composed of five elements: the human operator, the master manipulator, the communication channel, the slave manipulator and the environment. If the forces generated by the contact between the slave manipulator and the environment are reflected or transmitted back to the master as a part of its input torque, this teleoperation system is bilateral (Anderson and Spong, 1989). The communication delay is a major issue in bilateral teleoperation systems, which may induce instability (Anderson and Spong, 1989; Hokayem and Spong, 2006). Transparency is another challenge in bilateral teleoperacion. The transparency means the operator appropriately feels as if he is manipulating the remote object directly.

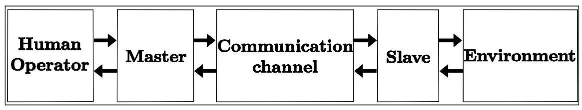

Fig. 1. Two-port structure of the bilateral teleoperation systems.

In bilateral teleoperation there are two major goals: stability and transparency. Achieving these goals generally improves the operator's ability to perform complex tasks. There are diverse control approaches to reach them. Over the past two decades, the researchers paid more and more attention to develop effective control schemes to solve the first issue: closed-loop stability in the

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bilateral teleoperation systems. One of the most important work is that the bilateral teleoperation systems are stable under arbitrary bounded constant time delay (Anderson and Spong, 1989). They used the transmitting scattering variables rather than the conventional power variables. A similar result proposed by Niemeyer and Slotine (1991) used wave variables to examine the dynamic property of a time delay teleoperation system. Under the framework of passivity based control, some further results have been presented to deal with the problems of time-varying delays (Niemeyer and Slotine, 1998; Yokokohji *et al*., 1999; Chopra *et al*., 2003). Munir (2002; 2003) used predictors to compensate the unfavorable effects generated by the time delay, such that higher dynamic performance be obtained. The high-frequency contact forces between the environment and the human operator were transmitted to upgrade transparency of the teloperator in the work of Tanner and Niemeyer (2005) .

There are several problems in the above results, such as the wave reflection and the position drift in the passivity based or scattering based approach proposed by Niemeyer and Slotine (1991; 2004) as well as Chopra *et al*. (2006). They induced the packet loss in an unreliable communication network or the time-varying communication delay. The wave reflection problem can be decreased via enforcing impedance matching or adding a wave filter in the communication channel (Niemeyer and Slotine, 1991; 2004). The position drift problem can be alleviated by transmitting both the wave variable and its integral (Niemeyer and Slotine, 1998; 2004), or incorporated the master-slave position tracking errors into the master-slave control inputs (Chopra *et al.*, 2006; 2008; Imaida *et al.*, 2004; Lee and Spong, 2006; Nuno *et al.*, 2008). Recent results show that the synchronization based approach can fundamentally solve the wave reflection and position drift problems that appears in the traditional scattering variable based approach (Imaida *et al*., 2004; Lee and Spong, 2006; Chopra *et al*., 2008; Nuno *et al*., 2008).

There are some methods using control theory. The Lyapunov-based approach can simplify the design process (Imaida *et al*., 2004; Lee and Spong, 2006). The transparency can be obtained by controller design, see the works by Lawrence (1993) or Yokokohji and Yoshikawa (1994), where the four-channel framework was proposed such that ideal transparency can be attained without any time delay in the communication channel. In order to avoid measuring acceleration in the four-channel control algorithm, Zhu and Salcudean (1995), Salcudean *et al*. (2000), and Mobasser and Hashtrudi-Zaad (2008) proposed position and rate control algorithms, at the expense of realizing sublevel transparency.

However, all the above papers do not consider haptic sensing in bilateral teleoperation. Without haptic guidance, it is very difficult to perform a precise teleoperation by the human operator. Impedance/admittance control is one of the most effective human-robot integration strategy (Wen and Murphy, 1991). Admittance defines a dynamic mapping from force to motion. An admittance device would sense the input force and "*admit*" a certain amount of motion. The admittance model from the human operator can be used to replace the master manipulator model in the local site. The object of the bilateral teleoperation with haptic feedback is the following: the robot manipulator and the human operator always have the same position and contract force. The human operator should feel that he grips the end-effector while he handles the teloperator,

The traditional control schemes do not have force controllers that allow a good interaction with the environment in hard contact. An improvement in the position tracking accuracy might give rise to larger contact forces, this problem disrupts the transparency of the closed-loop system during contact motion (Lee and Spong, 2006). The force control (Chiaverini *et al*., 1994) or the position tracking with impedance models (Nuno *et al*., 2008; Nuno and Basanez, 2009) can solve the above problems. Here the force control schemes require the dynamics and the inverse dynamics of robots (Nuno *et al*., 2010). Some control schemes were designed to enhance system transparency by using measured force signals in the control structure (Cho and Park, 2005; Ganjefar *et al*., 2017; Ishii and Katsura, 2012; Xu *et al*., 2016; Ousaid *et al*., 2015). On the other hand, recent works based on the passivity approach, controlling the energy flow at the input/output port are conservative (Rebelo and Schiele, 2015; Chen *et al*., 2018; Balachandran *et al*., 2016; Liu *et al*., 2018). In such cases, they just consider the stability and transparency to linear bilateral teleoperation systems.

But these position-force controllers do not have the analysis of the stability and transparency of nonlinear delayed bilateral teleoperation. In fact, there are special problems in the delayed bilateral teleoperation with haptic feedback. Force control could improve the interaction effect with the environment and avoid large contact forces. The stability is to guarantee stable transition contact. Thus we should transmit the force in conjunction with position signals to enhance a higher transparency.

In this paper, we propose a new control framework for a bilateral teloperator with time-varying communication delays. We include the human operator admittance model in the bilateral teleoperation system. Since the robotic dynamic is nonlinear, we analyze the stability and transparency of the nonlinear teleoperation systems.

The paper is organized as follows. Section 2 introduces the novel bilateral teleoperation system, which combines the human operator model and the delayed bilateral teleoperation model. Section 3 provides stability analysis with the Lyapunov–Krasovskii

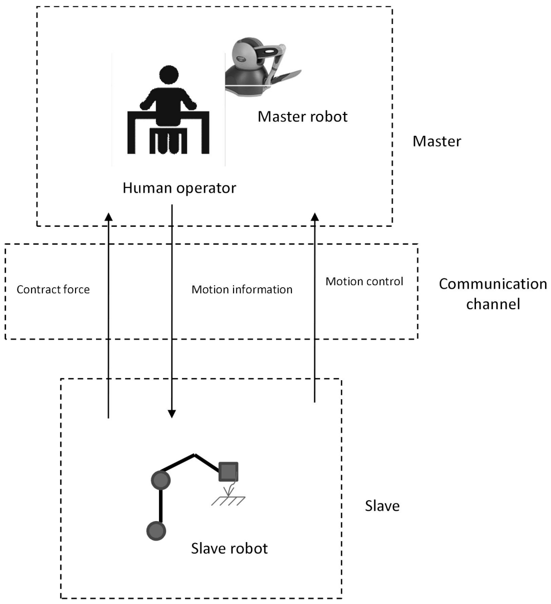

Fig. 2. Bilateral teleoperation with haptic feedback.

functional. Section 4 presents the transparency analysis in free motion and contact motion. In Section 5 simulations are reported to highlight the effectiveness of the novel bilateral teleoperation model and the control approach. Concluding remarks are given in Section 6.

2. Delayed bilateral teleoperation with haptic feedback

The dynamic model of the teleoperation system in the task space[1] is

$$M_m(x_m)\ddot{x}_m + C_m(x_m,\dot{x}_m)\dot{x}_m + g_m = f_m^* - f_h,$$
$$M_s(x_s)\ddot{x}_s + C_s(x_s,\dot{x}_s)\dot{x}_s + g_s = f_e - f_s^*.$$

According to the bilateral teleoperation, the model of the master robot should be replaced by the human operator model, see Fig. 2. Therefore, the bilateral teleoperation system based on admittance human operator model in the task space is

$$\begin{aligned} M_a\ddot{x}_m + B_a\dot{x}_m + K_a x_m &= f_m^* - f_h, \\ M_s(x_s)\ddot{x}_s + C_s(x_s,\dot{x}_s)\dot{x}_s + g_s &= f_e - f_s^*, \end{aligned} \tag{1}$$

where $\ddot{x}_i, \dot{x}_i, x_i,\ i = m, s$, are the acceleration, the velocity and the end-effector position of the master and slave robots, f_h, f_e are the operator and environment forces, respectively. f_m^*, f_s^* represent the control force inputs precompensated by the gravitational force and stiffness. M_a, B_a and K_a are the inertia, viscosity and stiffness constant positive matrices of human arm admittance, $M_s(x_s)$ is a symmetric and positive-definite inertia matrix, $C_s(x_s,\dot{x}_s)$ represent the Coriolis matrix of the slave system, and $g_s(x_s)$ is the vector of gravitational forces of the slave manipulator.

[1]The task space (or Cartesian space) is defined by the position and orientation of the end effector of a robot.

We use the following properties of the robotic model:

P1. The inertia matrix $M_s(x_s)$ is symmetric, positive definite and uniformly bounded by

$$0 < \lambda_{\min}\{M_s\} I \le M_s \le \lambda_{\max}\{M_s\} I < \infty \tag{2}$$

with $\lambda_{\min}\{M_s(x_s)\}, \lambda_{\max}\{M_s(x_s)\} \in \mathbb{R}^+$, the minimum and maximum eigenvalues of $M_s(x_s)$, respectively.

P2. For the Coriolis matrix $C_s(x_s,\dot{x}_s)$, there exists a number $k_c > 0$ such that

$$\|C_s(x_s,\dot{x}_s)\| \le k_c\|\dot{x}_s\|^2 \tag{3}$$

and $\dot{M}_s(x_s) - 2C_s(x_s,\dot{x}_s)$ is skew-symmetric, i.e.,

$$\dot{x}_s^T\left[\dot{M}_s(x_s) - 2C_s(x_s,\dot{x}_s)\right]\dot{x}_s = 0. \tag{4}$$

Teleoperation systems always have time delays in communication channels. We consider a variable time delay. Owing to the communication nature, it can not be negative and has a known upper bound $T_{i,\max}$, i.e.,

$$0 \le T_i(t) \le T_{i,\max} < \infty, \quad i = m, s. \tag{5}$$

For the task-space teleoperation, the system interacts with the human operator via the master robot, and with the environment via the end effector of the slave robot. We assume that the task-space interaction is passive. The assumption has been adopted by Lee and Spong (2006), Nuno *et al*. (2008) and Jafari *et al*. (2013). On the basis of the standard passivity notion (Lozano *et al*., 2007), there exist $\kappa_i \in \mathbb{R}^+$ such that for all $t \ge 0$,

$$\int_0^t \dot{x}_m^T f_h \,\mathrm{d}\sigma \ge -\kappa_m, \quad -\int_0^t \dot{x}_s^T f_e \,\mathrm{d}\sigma \ge -\kappa_s. \tag{6}$$

In order to simplify some calculations and focus on the main idea, we assume that the gravitational force and stiffness from the master and the slave models are precompensated by the controllers f_i^*, i.e., $f_m^* = f_m + g_m$ and $f_s^* = f_s + K_a x_s$, respectively. Hence, the dynamic model (1) changes to

$$\begin{aligned} M_a\ddot{x}_m + B_a\dot{x}_m &= f_m - f_h, \\ M_s(x_s)\ddot{x}_s + C_s(x_s,\dot{x}_s)\dot{x}_s &= f_e - f_s. \end{aligned} \tag{7}$$

Owing to lack of information about the variation in human and environment forces, we assume that the variation rate of these forces is bounded, i.e., $f_h,\ f_e \in \mathcal{L}_\infty$.

We expect to achieve the following control goals:

1. The bilateral teleoperation system is stable if the human operator and the environment are passive and their forces are bounded.

2. The master-slave kinematics in the free-motion case satisfy

$$x_m - x_s(t - T_s(t)) \to 0,$$
$$x_s - x_m(t - T_m(t)) \to 0$$

as $t \to \infty$.

3. The master-slave positions and forces in the contact motion case meet the requirement

$$x_m - x_s(t - T_s(t)) \to 0,$$
$$x_s - x_m(t - T_m(t)) \to 0,$$
$$f_h - f_e(t - T_s(t)) \to 0.$$

This is transparency.

In order to achieve the control goals described above, we propose the following sliding mode PD control law for the delayed bilateral teleoperation system:

$$\begin{aligned} f_m &= -P(x_m - x_s(t - T_s(t))) - B_m \dot{x}_m \\ &\quad - \alpha \,\mathrm{sgn}(\dot{x}_m) f_{he}^T f_{he}, \\ f_s &= P(x_s - x_m(t - T_m(t))) + B_s \dot{x}_s, \end{aligned} \tag{8}$$

where $\alpha > 0$, the sliding mode term $\alpha \mathrm{sgn}(\dot{x}_m)$ is used to cancel the uncertainties in the teleoperation system, the PD control gains P and B_i $(i = m, s)$ are positive definite matrices, $T_m(t)$ and $T_s(t)$ are the forward and backward communication time delays. Here

$$f_{he} = f_h - f_e[t - T_s(t)].$$

In addition, we assume that the upper bound of the round-trip delay $T_{r,\max} = T_{m,\max} + T_{s,\max}$ is known as a prior.

3. Stability of nonlinear bilateral teleoperation with force feedback

Stability is one of main bilateral teleoperation objectives; see the work of Lawrence (1993) for more detail. The original idea comes from the passivity of the teleoperation system (Hogan, 1985), where it is required that the human operator and the environment exhibit passive features.

According to the model dynamic of (7) as well as the control law (8), the stability of the closed-loop system is given in the following theorem.

Theorem 1. *The nonlinear bilateral teleoperation system (7) is controlled by the controller (8). It is stable if $Q \geq 0$, where Q is defined as*

$$\begin{aligned} Q &= \begin{bmatrix} Q_m & 0 \\ 0 & Q_s \end{bmatrix}, \\ Q_m &= B_m + B_a - T_{r,\max} P, \\ Q_s &= B_s - T_{r,\max} P. \end{aligned} \tag{9}$$

Proof. Consider a nonnegative Lyapunov–Krasovskii functional,

$$V(t) = \sum_{k=1}^{5} V_k(t),$$

where

$$V_1(t) = \frac{1}{2}\dot{x}_m^T M_a \dot{x}_m + \frac{1}{2}\dot{x}_s^T M_s(x_s)\dot{x}_s, \tag{10}$$

$$V_2(t) = \frac{1}{2}(x_m - x_s)^T P (x_m - x_s), \tag{11}$$

$$V_3(t) = \sum_{i=m,s}\left[\int_{-T_{i,\max}}^{0}\int_{t+\theta}^{t} \dot{x}_i^T P \dot{x}_i \,\mathrm{d}\sigma\,\mathrm{d}\theta\right], \tag{12}$$

$$V_4(t) = \int_0^t \left(\dot{x}_m^T f_h - \dot{x}_s^T f_e\right)\mathrm{d}\sigma + \kappa_m + \kappa_s, \tag{13}$$

$$V_5(t) = \alpha \int_0^t \dot{x}_m \mathrm{sgn}(\dot{x}_m) f_{he}^T f_{he}\,\mathrm{d}\theta. \tag{14}$$

In the Lyapunov–Krasovskii functional, $V_1(t)$ represents the kinetic energy of the master and slave robots, $V_2(t)$ corresponds to the energy stored in the proportional control term, $V_3(t)$ is related to the network delay, $V_4(t)$ includes the energies input by the operator and environment and $V_5(t)$ corresponds to the force control term.

If we apply (4) in Property II to the teleoperation dynamic system (7), the time derivative of V_1 is simplified as

$$\dot{V}_1(t) = \dot{x}_m^T(f_m - f_h - B_a\dot{x}_m) + \dot{x}_s^T(f_e - f_s). \tag{15}$$

Adding $\dot{x}_m P(x_s(t - T_s(t)) - x_s(t - T_s(t)))$ and $\dot{x}_s P(x_m(t - T_m(t)) - x_m(t - T_m(t)))$ to the time derivative of (11) results in

$$\begin{aligned} \dot{V}_2(t) &= -\dot{x}_m P \int_{t-T_s(t)}^{t} \dot{x}_s\,\mathrm{d}\theta - \dot{x}_s P \int_{t-T_m(t)}^{t} \dot{x}_m\,\mathrm{d}\theta \\ &\quad + \dot{x}_m P(x_m - x_s(t - T_s(t))) \\ &\quad + \dot{x}_s P(x_s - x_m(t - T_m(t))). \end{aligned} \tag{16}$$

After some algebra the time derivative of (12) can be expressed as

$$\dot{V}_3(t) \leq \sum_{i=m,s}\left[T_{i,\max}\dot{x}_i^T P \dot{x}_i - \int_{t-T_i(t)}^{t} \dot{x}_i^T P \dot{x}_i\,\mathrm{d}\theta\right]. \tag{17}$$

Applying the inequalities

$$\begin{aligned} &-\dot{x}_m P \int_{t-T_s(t)}^{t} \dot{x}_s\,\mathrm{d}\theta - \int_{t-T_s(t)}^{t} \dot{x}_s^T P \dot{x}_s\,\mathrm{d}\theta \\ &\qquad \leq T_{s,\max}\dot{x}_m^T P \dot{x}_m \end{aligned}$$

and

$$-\dot{x}_s P \int_{t-T_m(t)}^{t} \dot{x}_m \, \mathrm{d}\theta - \int_{t-T_m(t)}^{t} \dot{x}_m^T P \dot{x}_m \, \mathrm{d}\theta \le T_{m,\max} \dot{x}_s^T P \dot{x}_s,$$

the sum $\dot{V}_2(t) + \dot{V}_3(t)$ from Eqns. (16) and (17) is simplified as

$$\begin{aligned}\dot{V}_{23}(t) \le T_{r,\max} \left(\sum_{i=m,s} \dot{x}_i^T P \dot{x}_i \right) \\ + \dot{x}_m P (x_m - x_s(t - T_s(t))) \\ + \dot{x}_s P (x_s - x_m(t - T_m(t))) .\end{aligned} \tag{18}$$

Therefore, the time derivatives of (13) and (14) are

$$\dot{V}_4(t) = \dot{x}_m^T f_h - \dot{x}_s f_e \tag{19}$$

and

$$\dot{V}_5(t) = \alpha \dot{x}_m \operatorname{sgn}(\dot{x}_m) f_{he}^T f_{he}, \tag{20}$$

respectively.

The sum $\dot{V}(t) = \sum_{k=1}^{5} \dot{V}_k(t)$, given by (15) and (18)–(20) can be written as

$$\begin{aligned}\dot{V}(t) \le \dot{x}_m^T (f_m - f_h - B_a \dot{x}_m) + \dot{x}_s^T (f_e - f_s) \\ + T_{r,\max} \Big(\sum_{i=m,s} \dot{x}_i^T P \dot{x}_i \Big) + \dot{x}_m^T f_h - \dot{x}_s f_e \\ + \dot{x}_m P (x_m - x_s(t - T_s(t))) \\ + \dot{x}_s P (x_s - x_m(t - T_m(t))) \\ + \alpha \dot{x}_m \operatorname{sgn}(\dot{x}_m) f_{he}^T f_{he}.\end{aligned} \tag{21}$$

Using the control law (8), we reduce the last equation to

$$\dot{V}(t) \le -\dot{x}^T Q \dot{x} \le 0, \tag{22}$$

where $Q = \operatorname{diag}\{Q_m, Q_s\} \ge 0$, such that $Q_m = B_m + B_a - T_{r,\max} P$ and $Q_s = B_s - T_{r,\max} P$. If $Q \ge 0$ we can guarantee the boundedness of the Lyapunov-Krasovskii functional. Therefore, we can conclude that

$$\dot{x}_m \in \mathcal{L}_\infty, \quad \dot{x}_s \in \mathcal{L}_\infty, \quad x_m - x_s \in \mathcal{L}_\infty.$$

According to the above discussion, the control system is stable in the presence of time delay in communication channels. ■

4. Transparency of nonlinear bilateral teleoperation

The transparency is another major goal in teleoperation systems. When the teleoperation has haptic feedback, the transparency includes positions and forces between the master and slave robots (Yokokohji and Yoshikawa, 1994; Salcudean *et al.*, 2000), and the impedances perceived by the operator and the environment (Lawrence, 1993).

Both the human operator and the environment are in contact with the master and slave robots; see Fig. 2. The conditions for kinematic correspondence $x_m \equiv x_s$ as well as for force matching are

$$f_{te}|_{f_h^*=0} = f_h, \quad f_{to}|_{f_e^*=0} = f_e,$$

where f_{te} and f_{to} are the forces transmitted by the human operator and the environment, and f_h^* and f_e^* are the operator and environment exogenous force inputs.

If the time delay in the communication channel is negligible, the performances of the position and force between the master and slave robots are prefect. In practice, the delays affect the velocities generated by the operator or caused by the environment. Therefore we need

$$\begin{aligned}x_m - x_s(t - T_s(t)) \to 0, \\ f_h - f_e(t - T_s(t)) \to 0,\end{aligned}$$

where $f_h^* = 0$, and

$$\begin{aligned}x_s - x_m(t - T_m(t)) \to 0, \\ f_e - f_h(t - T_m(t)) \to 0\end{aligned}$$

for $f_e^* = 0$.

For the four channels the bilateral teleoperation system (see Fig. 1), we use the following three-channel scheme, where there are no environment exogenous forces ($f_e^* = 0$). The transparency conditions are

$$\begin{aligned}x_m - x_s(t - T_s(t)) \to 0, \\ f_h - f_e(t - T_s(t)) \to 0\end{aligned} \tag{23}$$

for $f_h^* = 0$, and

$$x_s - x_m(t - T_m(t)) \to 0 \tag{24}$$

for $f_e^* = 0$.

4.1. Free motion without force feedback.

We assume the operator and environment forces to be equal zero, i.e., $f_h = f_e = 0$.

Theorem 2. *The position error in free motion converges to zero with respect to the control scheme (8), i.e.,*

$$\begin{aligned}x_m - x_s(t - T_s(t)) \to 0, \quad t \to \infty, \\ x_s - x_m(t - T_m(t)) \to 0, \quad t \to \infty.\end{aligned}$$

Thus the transparency in kinematics is achieved.

Proof. In stability analysis, we conclude that $\dot{x}_m$, $\dot{x}_s$ and $x_m - x_s$ are bounded. Integrating both the sides of (22), we get the following expression:

$$V(t) - V(0) \le -\int_0^t \dot{x}^T Q \dot{x} \, \mathrm{d}\theta.$$

It can be rewritten as

$$\int_0^t \dot{x}^T Q \dot{x}\, \mathrm{d}\theta \leq V(0) - V(t) \leq V(0) < +\infty.$$

This means

$$\dot{x}_i \in \mathcal{L}_2.$$

With the condition $Q \geq 0$, we can conclude that

$$\dot{x}_i \in \mathcal{L}_2 \cap \mathcal{L}_\infty.$$

Hence $\dot{x}_i$ is uniformly continuous and will converge to zero. From the equation

$$\begin{aligned} x_m - x_s(t - T_s(t)) = x_m - x_s + x_s \\ - x_s(t - T_s(t)) \end{aligned} \tag{25}$$

we get

$$\begin{aligned} x_s - x_s(t - T_s(t)) &= \int_0^{T_s(t)} \dot{x}_s(t+\theta)\, \mathrm{d}\theta \\ &\leq T_{s,\max}^{1/2} \|\dot{x}_s\|_2 \end{aligned} \tag{26}$$

after applying the Schwartz inequality. Using (25) and (26), we deduce that

$$x_m - x_s(t - T_s(t)) \in \mathcal{L}_\infty.$$

With the same computations, we obtain

$$x_s - x_m(t - T_m(t)) \in \mathcal{L}_\infty.$$

The teleoperation dynamic equation (7) and the proposed control low (8) with $f_h = f_e = 0$ can be written as

$$\begin{aligned} \ddot{x}_m &= -M_a^{-1}\left[P(x_m - x_s(t - T_s(t))) \right. \\ &\quad \left. + B_m \dot{x}_m + B_a \dot{x}_m\right], \\ \ddot{x}_s &= -M_s^{-1}(x_s)\left[P(x_s - x_m(t - T_m(t))) \right. \\ &\quad \left. + B_s \dot{x}_s + C_s(x_s, \dot{x}_s)\dot{x}_s\right]. \end{aligned} \tag{27}$$

From (27), Properties P1 and P2, we can deduce that

$$\ddot{x}_i \in \mathcal{L}_\infty.$$

The position synchronization arrives if $\ddot{x} \to 0$ is proven. The time derivative of (27) is

$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}t}\ddot{x}_m = -M_a^{-1}\frac{\mathrm{d}}{\mathrm{d}t}\left[P(x_m - x_s(t - T_s(t))) \right. \\ \left. + B_m \dot{x}_m + B_a \dot{x}_m\right] \end{aligned} \tag{28}$$

and

$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}t}\ddot{x}_s = -\frac{\mathrm{d}}{\mathrm{d}t}M_s^{-1}(x_s)&\left[P(x_s - x_m(t - T_m(t))) \right. \\ &\left. + B_s \dot{x}_s + C_s(x_m, \dot{x}_m)\dot{x}_s\right] \\ - M_s^{-1}(x_s)\frac{\mathrm{d}}{\mathrm{d}t}&\left[P(x_s - x_m(t - T_m(t))) \right. \\ &\left. + B_s \dot{x}_s + C_s(x_m, \dot{x}_m)\dot{x}_s\right]. \end{aligned} \tag{29}$$

The first term from (29) is

$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}t}M_s^{-1}(x_s) &= -M_s^{-1}(x_s)\dot{M}_s(x_s)M_s^{-1}(x_s) \\ &= -M_s^{-1}(x_s)\left[C_s(x_s, \dot{x}_s) \right. \\ &\quad \left. + C_s^T(x_s, \dot{x}_s)\right]M_s^{-1}(x_s). \end{aligned}$$

By using Properties P1 and P2, $\mathrm{d}M_s^{-1}/\mathrm{d}t$ is bounded. Evidently (28) and (29) are bounded. In consequence,

$$(\mathrm{d}/\mathrm{d}t)\,\ddot{x}_i \in \mathcal{L}_\infty.$$

Therefore $\ddot{x}_i$ are uniformly continuous. Hence

$$\int_0^t \ddot{x}_i \mathrm{d}\theta = \dot{x}_i(t) - \dot{x}_i(0).$$

Since $\dot{x}_i \to 0$, $\int_0^\infty \ddot{x}_i\, \mathrm{d}\theta$ is bounded. Using Barbalat' lemma, we conclude that

$$\ddot{x}_i \to 0.$$

Owing to

$$\dot{x}_i \to 0, \quad \ddot{x}_i \to 0$$

the master and slave position synchronization is achieved as

$$\begin{aligned} \lim_{t\to\infty} x_m - x_s(t - T_s(t)) \to 0, \\ \lim_{t\to\infty} x_s - x_m(t - T_m(t)) \to 0. \end{aligned}$$

Accordingly, the position error converges to zero in free motion. ■

4.2. Motion with contract forces.

In this case, the operator and environment forces are assumed to be bounded, i.e., $f_h \in \mathcal{L}_\infty$ and $f_e \in \mathcal{L}_\infty$.

Theorem 3. *The position and force errors in the teleoperation system converge to zero with the control scheme (8) as $t \to \infty$, i.e.,*

$$\begin{aligned} x_m - x_s(t - T_s(t)) \to 0, \\ x_s - x_m(t - T_m(t)) \to 0, \\ f_h - f_e(t - T_s(t)) \to 0. \end{aligned}$$

Proof. Since the gravity $g_s(x_s)$ and the stiffness $K_a x_m$ are bounded, and the forces are assumed to be bounded, it is possible to assume that f_m and f_s in (8) are also bounded. The teleoperation dynamic equation (7) and the proposed law control(8) can be rewritten as

$$\begin{aligned} \ddot{x}_m &= -M_a^{-1}\left[P(x_m - x_s(t - T_s(t))) + B_m \dot{x}_m \right. \\ &\quad \left. + B_a \dot{x}_m + f_h + \alpha \mathrm{sgn}(\dot{x}_m) f_{he}^T f_{he}\right], \\ \ddot{x}_s &= -M_s^{-1}(x_s)\left[P(x_s - x_m(t - T_m(t))) \right. \\ &\quad \left. + B_s \dot{x}_s - f_e + C_s(x_s, \dot{x}_s)\dot{x}_s\right]. \end{aligned} \tag{30}$$

Since $\dot{x}_i \in \mathcal{L}_2 \cap \mathcal{L}_\infty$, $x_m - x_s(t - T_s(t)), x_s - x_m(t - T_m(t)) \in \mathcal{L}_\infty$, $f_h, f_e \in \mathcal{L}_\infty$, using Properties P1 and P2, we can conclude that

$$\ddot{x}_m \in \mathcal{L}_\infty, \quad \ddot{x}_s \in \mathcal{L}_\infty.$$

Therefore, due to Barbalat's lemma,

$$\dot{x}_i \to 0.$$

The time derivative of (30) is

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t}\ddot{x}_m = -M_a^{-1}\frac{\mathrm{d}}{\mathrm{d}t}\big[&P\left(x_m - x_s\left(t - T_s\left(t\right)\right)\right)\\ &+B_m\dot{x}_m + B_a\dot{x}_m + f_h\\ &+\alpha\,\mathrm{sgn}\left(\dot{x}_m\right) f_{he}^T f_{he}\big],\end{aligned} \tag{31}$$

and

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t}\ddot{x}_s = -&\frac{\mathrm{d}}{\mathrm{d}t}M_s^{-1}\left(x_s\right)\left[P\left(x_s - x_m\left(t - T_m\left(t\right)\right)\right)\right.\\ &\left.+B_s\dot{x}_s - f_e + C_s\left(x_s, \dot{x}_s\right)\dot{x}_s\right]\\ &- M_s^{-1}\left(x_s\right)\frac{\mathrm{d}}{\mathrm{d}t}\left[P\left(x_s - x_m\left(t - T_m\left(t\right)\right)\right)\right.\\ &\left.+B_s\dot{x}_s - f_e + C_s\left(x_s, \dot{x}_s\right)\dot{x}_s\right].\end{aligned} \tag{32}$$

The first term of (32) is

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t}M_s^{-1}\left(x_s\right) &= -M_s^{-1}\left(x_s\right)\dot{M}_s\left(x_s\right)M_s^{-1}\left(x_s\right)\\ &= -M_s^{-1}\left(x_s\right)\left[C_s\left(x_s, \dot{x}_s\right)\right.\\ &\quad\left.+C_s^T\left(x_s, \dot{x}_s\right)\right]M_s^{-1}\left(x_s\right).\end{aligned}$$

By using Properties P1 and P2, $\mathrm{d}M_s^{-1}/\mathrm{d}t$ are bounded. Evidently, (31) and (32) are bounded. In consequence, $(\mathrm{d}/\mathrm{d}t)\,\ddot{x}_i \in \mathcal{L}_\infty$. Therefore $\ddot{x}_i$ are uniformly continuous. Using Barbalat's lemma, we can conclude that

$$\ddot{x}_i \to 0.$$

As $\dot{x}_i \to 0$ and $\ddot{x}_i \to 0$ in the dynamic slave teleoperation system, we get

$$\begin{aligned}P\left(x_s - x_m\left(t - T_m\left(t\right)\right)\right) - f_e \to 0,\\ P\left(x_m - x_s\left(t - T_s\left(t\right)\right)\right) + f_h \to 0.\end{aligned}$$

Consequently,

$$\begin{aligned}x_s - x_m\left(t - T_m\left(t\right)\right) \to 0,\\ x_m - x_s\left(t - T_s\left(t\right)\right) \to 0.\end{aligned}$$

Now we apply the last results, i.e.,

$$\begin{aligned}x_i &\to 0\\ x_m - x_s\left(t - T_s\left(t\right)\right) &\to 0,\\ x_m - x_s\left(t - T_s\left(t\right)\right) &\to 0.\end{aligned}$$

The teleoperation system (7) with the control law (8) are simplified

$$M_a\ddot{x}_m = \varepsilon\left(f_h - f_e\left(t - T_s\left(t\right)\right)\right)^T\left(f_h - f_e\left(t - T_s\left(t\right)\right)\right)$$

Premultiplying both the sides by $\varepsilon^T M_a^{-1}$, we get

$$\begin{aligned}\varepsilon^T\ddot{x}_m = \varepsilon^T M_a^{-1}\varepsilon&\left(f_h - f_e\left(t - T_s\left(t\right)\right)\right)^T\\ \cdot&\left(f_h - f_e\left(t - T_s\left(t\right)\right)\right).\end{aligned}$$

Using Property P1 and $1/\left(\lambda_{\max}\left\{M_a\right\}\right)I \le M_a^{-1}$, we have

$$\begin{aligned}\varepsilon^T\ddot{x}_m \ge \frac{1}{\lambda_{\max}\left\{M_a\right\}}&\|\varepsilon\|_2^2\left(f_h - f_e\left(t - T_s\left(t\right)\right)\right)^T\\ \cdot&\left(f_h - f_e\left(t - T_s\left(t\right)\right)\right).\end{aligned}$$

Note that $\left(f_h - f_e\left(t - T_s\left(t\right)\right)\right)^T\left(f_h - f_e\left(t - T_s\left(t\right)\right)\right)$ and $\|\varepsilon\|_2^2$ are nonnegative, and $\lambda_{\max}\left\{M_a\right\}$ is positive.

If $\varepsilon^T\ddot{x}_m = 0$, we have

$$f_h - f_e\left(t - T_s\left(t\right)\right) = 0$$

and the proof is completed.

If $\varepsilon^T\ddot{x}_m > 0$, in view of the fact that all the elements of ε^T are positive, there exist positive $\ddot{x}_{m_i}$ as $t \to \infty$,

$$\sum_{i=1}^{n}\ddot{x}_{m_i} > 0.$$

But this is a contradiction with $\dot{x}_m \to 0$. Therefore $\varepsilon^T\ddot{x}_m$ tends to zero and $f_h - f_e\left(t - T_s\left(t\right)\right) \to 0$. The tracking error of the force converges to zero. ■

5. Simulations

In order to verify the proposed theoretical results, the slave manipulator is considered to be a 2-DOF planar robot with revolute joints. The slave manipulator dynamics have the following inertia matrix (Lee and Li, 2005)

$$M_s\left(q_s\right) = \begin{bmatrix}\alpha + 2\beta\cos\left(q_2\right) & \delta + \beta\cos\left(q_2\right)\\ \delta + \beta\cos\left(q_2\right) & \delta\end{bmatrix}$$

where q_k is the articular position of each link with $k \in 1, 2$, $\alpha = l_2^2 m_2 + l_1^2\left(m_1 + m_2\right)$, $\beta = l_1 l_2 m_2$, and $\delta = l_2^2 m_2$. The lengths for both links l_1 and l_2 in the manipulator are 0.5 m, for simplicity. The masses for each link correspond to $m_1 = 3.24$ kg, and $m_2 = 0.31$ kg, respectively. Coriolis and centrifugal forces are modeled as the vector

$$C_s\left(q_s, \dot{q}_s\right) = \begin{bmatrix}-\beta\sin\left(q_2\right)\dot{q}_2^2 - 2\beta\sin\left(q_2\right)\dot{q}_1\dot{q}_2\\ \beta\sin\left(q_2\right)\dot{q}_1^2\end{bmatrix},$$

where $\dot{q}_k$ are the respective revolute velocities of the two links. The gravity effects are represented by

$$g_s\left(q_s\right) = g\begin{bmatrix}\frac{1}{l_2}\delta\cos\left(q_1 + q_2\right) + \frac{1}{l_1}\left(\alpha - \delta\right)\cos\left(q_1\right)\\ \frac{1}{l_2}\delta\cos\left(q_1 + q_2\right)\end{bmatrix}.$$

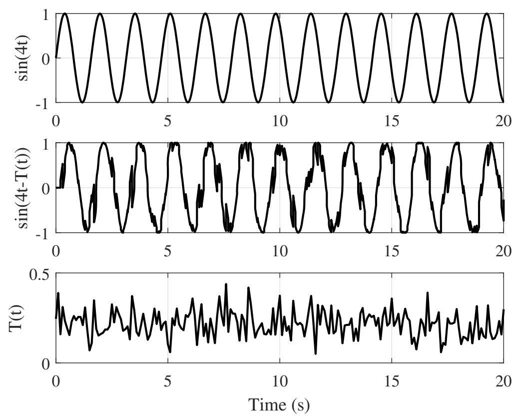

Fig. 3. Delayed signal with a variable time delay.

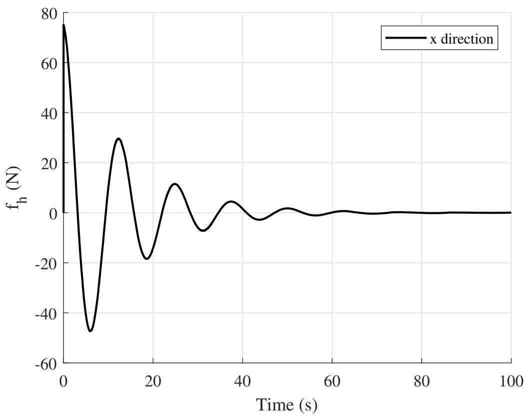

Fig. 4. Human force f_h is applied to the master robot in the x direction.

It should be clarified that the human exerts a force on the local manipulator's tip, and the remote manipulator interaction with the environment is also measured at its tip. Hence, for the simulations, we use the expression

$$\tau_e = J_s^T\left(q_s\right) f_e$$

where $J_s\left(q_s\right)$ is the Jacobian of the slave robot manipulator.

The admittance human operator model has the following inertia, stiffness and damping matrix gains (Lawrence, 1993)

$$\begin{aligned} M_a &= \operatorname{diag}\{17.5, 17.5\} \text{ N}, \\ B_a &= \operatorname{diag}\{175, 175\} \text{ N/m}, \\ K_a &= \operatorname{diag}\{175, 175\} \text{ Ns/m}. \end{aligned}$$

The gains of the controller are $P = 50I$, $B_i = 10I$, where I is the identity matrix, and $T_{i,\max} = 0.45\,\text{s}$, which clearly fulfills the stability condition. The initial positions for the local and remote manipulators are $x_m(0) = [0,0]^T$ and $x_s(0) = [0,0]^T$, whereas the initial velocities are zero.

For simplicity, the variable time delays are the same for both forward and backward paths. Figure 3 shows how a sinusoidal signal is sent through variable time delay from the local robot to the remote robot.

5.1. Simulation for free motion. We first show that the position tracking errors (kinematic in free motion) converge, i.e.,

$$\begin{aligned} x_m - x_s\left(t - T_s(t)\right) &\to 0, \\ x_s - x_m\left(t - T_m(t)\right) &\to 0. \end{aligned}$$

It is a free motion. The slave robot does not contact with the environment, so that $f_e = 0$. The human's force f_h applied to the master robot along the x direction is shown in Fig. 4. The force applied along the y direction is null. After a while, f_h decreases to zero. The position tracking of the master and the slave sites are shown in Fig. 5. We can see that the tracking errors converge to zero.

From the simulation, we can conclude that

- The bilateral teleoperation system is stable in free motion.
- Transparency (kinematic correspondence) is guaranteed.
- There is a good performance in free motion.

The following simulations will show that the bilateral teleoperation system with the control law can guarantee stability and transparency with contact forces.

5.2. Simulation for contact force. The simulations show that we can guarantee a stable bilateral teleoperation

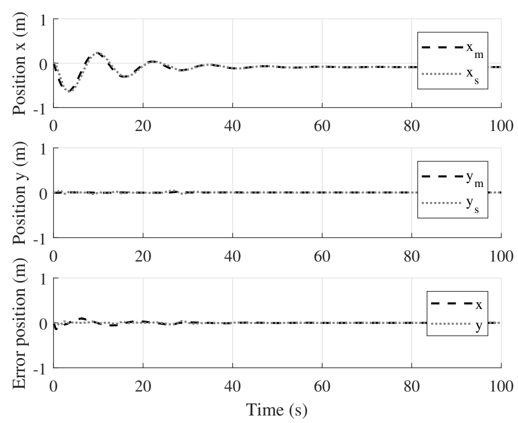

Fig. 5. Position tracking between the local and remote sites.

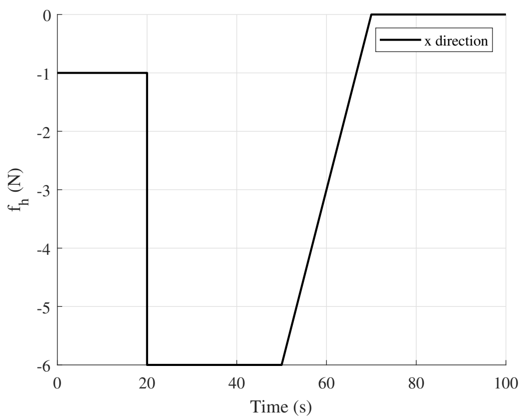

Fig. 6. Human's force f_h is applied to the master robot in the x direction.

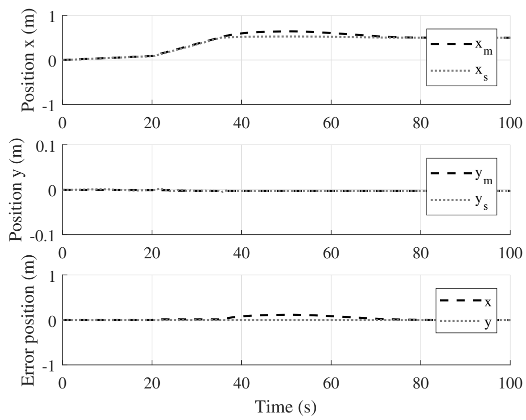

Fig. 7. Position tracking between the local and remote sites.

in transition motion. Also, we improve the transparency in the three-channel architecture, i.e.,

$$x_m - x_s\left(t - T_s\left(t\right)\right) \to 0,$$
$$x_s - x_m\left(t - T_m\left(t\right)\right) \to 0,$$
$$f_h - f_e\left(t - T_s\left(t\right)\right) \to 0$$

In order to evaluate the contact force, we implement a wall in the slave environment at 0.5 m. It is modeled as a spring-damper system along the x direction. The spring and damping gains are 200 N/m and 0.1 Ns/m. There is no exogenous force in environment, that is, the wall is static. The force is applied by a human, see Fig. 6. For a period of 20 s, the human operator stabilizes the master robot with 0.5 N. In the time interval from 20 to 50 s, the human pushes the master robot with the force 3 N to make a hard contact. Finally, in the time interval from 50 to 90 s, the human retracts slowly until the zero force. The scenario is presented in Fig. 6. As in free motion simulation, we just apply force in the x direction. In Fig. 7 we can see the position errors of the master and the slave sites.

Figure 8 shows the force correspondence. We can see that when the robot touches the wall, and transmits back the force to the human operator, our controller improves the control performances, and

$$f_h - f_e\left(t - T_s\left(t\right)\right) \to 0.$$

This yields transparency.

The main problems in bilateral teleoperation systems with force feedback occur in contact motion and transition motion. We have the following remarks:

- Bilateral teleoperation system is stable in contact motion.
- Transparency (kinematic and force correspondences) is guaranteed,

$$x_m - x_s\left(t - T_s\left(t\right)\right) \to 0, \tag{33}$$
$$x_s - x_m\left(t - T_m\left(t\right)\right) \to 0. \tag{34}$$

5.3. Discussion. The novel scheme for the bilateral teleoperation system based on a human model can improve transparency in free and contact motions. For delayed bilateral teleoperation with haptic feedback, we have the following remarks:

- Perfect transparency does not exist in bilateral teleoperation because of a time delay in the communication channel. But our control law in task space can improve it.
- The control law has a small gain. This gain allows us to reduce the force error. The quadratic error of the force depends on human and environment forces. When it is bigger, the quadratic force increases, and

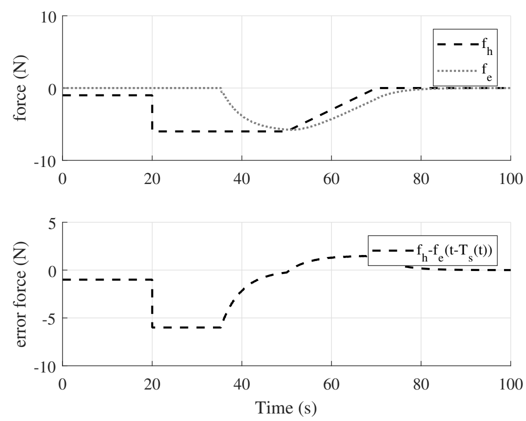

Fig. 8. Force tracking between the local and remote sites.

a motion transition may happen. We consider a small fixed gain to avoid a large contact force, because we do not know the contact force. A variable gain would help us to improve the motion transition, such that it is increased in a smooth contact.

- The parameters of the human model are constant. But these parameters depend on the motion and the operators. Therefore, it is necessary to develop an adaptive algorithm.
- In most scenarios the environment is unknown. A force estimator on the slave side would help to improve the performance.

Stability analysis based on Lyapunov's method is less conservative than passivity-based approaches, although it still involves great challenges to be solved. In the control of nonlinear robots in teleoperation there is no mathematical proof for a PID control based on the Lyapunov method. In the position/force control it has not been shown yet that exponential stability can be achieved.

In this work, no specific kind of disturbances has been considered. Is well known that robotic systems are subject to different types of disturbances, such as inertial parameter variations, friction, dynamic uncertainties and noise that affect stability and transparency directly. In practical robotic applications, ideal dynamic models are impossible to derive, while sensors may introduce large noise, especially force sensors that amplify noise, which results in a noisy force signal transmitted via time-delay communication for control. In consequence, mounting force sensors on a robot yields some limitations. In order to overcome this problem, force observers have been gradually deployed in teleoperation systems. This topic will be considered in our scheme as future work.

6. Conclusion

This paper studies the stability and transparency of bilateral teleoperation. Teleoperation systems have nonlinear bilateral, time-varying time delays and force feedback. By using the Lyapunov–Krasovskii method and task space admittance control, the stability and transparency of a closed-loop system are guaranteed. The performance of the proposed control method is evidenced by simulations. It has been shown that the controller presented in this paper improves the performance of the bilateral teleoperation.

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