Delay-independent stabilization for teleoperation with time varying delay

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Delay-Independent Stabilization for Teleoperation with Time Varying Delay

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Abstract— **This paper deals with the stability for nonlinear teleoperation with time varying communication delays. The proposed method is passivity-based controllers with time varying gains which depend on the rate of change of time varying delay. In our proposed method, stability condition is independent of the magnitude of the communication delay and the damping of the system. The delay-independent stability is shown via Lyapunov stability methods. Several experimental results show the effectiveness of our proposed teleoperation.**

I. INTRODUCTION

Teleoperation is the extension of a person's sensing and manipulation capability to a remote location and it has been tackled by researchers in control theory and robotics over the last few decades. A teleoperation is a dual robot system which a remote slave robot tracks the motion of a master robot that is commanded by a human operator. To improve the task performance, information about the remote environment is needed. In particular, force feedback from the slave to the master, representing contact information, provides a more extensive sense of telepresence. When this is applied, teleoperation is said to be controlled bilaterally [1].

In bilateral teleoperation, the master and the slave manipulators are coupled via a communication network and time delay occurs in transmission of data between the master and slave site. It is well known that the delays in a close loop system can destabilize an otherwise stable system. Recently, essential research interest is attracted by using the Internet as a communication network for teleoperation. Using the internet for communication line provides obvious benefits in terms of low cost and availability. However, this communication line caused time varying delays due to such factors as congestion, bandwidth or distance. These varying delays may degrade performance or even result in an unstable system. We refer to [1] for a detailed survey of the various schemes developed for the problem of bilateral teleoperation and their stability analysis. Therefore, we restrict ourselves to the discussion of passivity-based methods in bilateral teleoperation.

Stabilization for a teleoperation with constant delays has been achieved by scattering transformation based on the idea of passivity [2]. Then, the additional structure with position feedforward/feedback controls has proposed to improve the position coordination and force reflection performance [3], [4]. In [5], [6], [7], the P or PD-type controller without scattering transformation has been proposed which guarantees the stability for the constant communication delay. In these methods, the position coordination and force reflection have also been achieved by explicit position feedforward/feedback control. In these methods, however, teleoperation with time varying delays has not been guaranteed the stability.

Several researchers have addressed a problem of the teleoperation with time varying delays and several control methods based on scattering transformation have been reported. Some preliminary results are contained in [8], [9]. In [10], a simple modification of the scattering transformation has been proposed. The modification is inserting time varying gains which depend on the rate of change of time delay into the communication block to guarantee the passivity. In [11], then, a explicit position feedforward control was added to improve the position coordination. In [11], however, the position control gain is not possible to design arbitrarily, because it is limited to the damping of the system. This is a severe constraint for position coordination. In [12], it have proposed control methods without the scattering transformation. The proposed strategies were a couple of simple PD-type controllers. However, the position control gains depend on the upper bound of round-trip delay. When we use the internet as a communication network, we assume that the round-trip delay increase unpredictably. This may cause destabilization of teleoperation system.

In this paper, we propose the control strategy for nonlinear teleoperation with time varying delay. The proposed method is a novel passivity based controller that introduces the time varying gains [10], [11] to the conventional passivity based controller [7], [13]. In the proposed control strategy, stability condition is independent of the magnitude of the time delay and the damping of the system. So we can design control parameters appropriately. Using Lyapunov theory, the delay-independent stability of the origin is shown. Experimental results show the effectiveness of our proposed method.

II. DYNAMICS OF TELEOPERATION

In this paper, we consider a pair of nonlinear robotic systems coupled via communication line with time varying delay. Assuming absence of friction or other disturbances, Euler-Lagrange equations of motion for a n-link master and slave robot are given as

$$\begin{cases} M_m(q_m)\ddot{q}_m + C_m(q_m,\dot{q}_m)\dot{q}_m + B_m\dot{q}_m = \tau_m + J_m^T F_{op} \\ M_s(q_s)\ddot{q}_s + C_s(q_s,\dot{q}_s)\dot{q}_s + B_s\dot{q}_s = \tau_s - J_s^T F_{env} \end{cases} \tag{1}$$

where the subscript "m" and "s" denote the master and the slave index, q_m, $q_s \in \mathcal{R}^{n\times 1}$ are the joint angle vectors, $\dot{q}_m$,

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$\dot{q}_s \in \mathcal{R}^{n\times 1}$ are the joint velocity vectors, τ_m, $\tau_s \in \mathcal{R}^{n\times 1}$ are the applied torques, $F_{op} \in \mathcal{R}^{n\times 1}$ is the operator force vector applied to the master by human operator, $F_{env} \in \mathcal{R}^{n\times 1}$ is the environmental force vector acting on the slave robot when in contacts the environment, M_m, $M_s \in \mathcal{R}^{n\times n}$ are the inertia matrices, $C_m\dot{q}_m$, $C_s\dot{q}_s \in \mathcal{R}^{n\times 1}$ are the centripetal and Coriolis torques and B_m, $B_s \in \mathcal{R}^{n\times n}$ are the damping of the system. Below, we list here fundamental properties of the master and slave robots [14] that we use in the subsequent analysis

Property 1: The inertia matrix $M_i(q)$ $(i = m, s)$ is symmetric positive definite matrix which verifies

$$\lambda_m I \leq M_i(q_i) \leq \lambda_M I \tag{2}$$

where λ_m ($\lambda_M < \infty$) denotes the strictly positive minimum (maximum) eigenvalue of M_i for all configurations q_i.

Property 2: Under an appropriate definition of the matrix C_i, the matrix $\dot{M}_i - 2C_i$ is skew symmetric.

Property 3: The Coriolis and centrifugal terms $C_i(q_i, \dot{q}_i)\dot{q}_i$ verify

$$\|C_i(q_i, \dot{q}_i)\dot{q}_i\| \leq c_0\|\dot{q}_i\|^2 \tag{3}$$

for some bounded constant $c_0 > 0$.

For the human operator and the remote environment, we assume that

Assumption 1: The human operator and the remote environment can be modeled as passive system.

Under above assumption, the human operator is described as follows

$$\int_0^t -F_{op}^T(\xi) r_m(\xi) d\xi \geq 0 \tag{4}$$

And the remote environment is described as follows

$$\int_0^t F_{env}^T(\xi) r_s(\xi) d\xi \geq 0 \tag{5}$$

where r_m, $r_s \in \mathcal{R}^{n\times 1}$ are the input vectors to the operator and the environment, respectively.

Assumption 2: The operator and the environmental force are bounded by functions of the signals r_m and r_s respectively.

For the communication line, we assume that the forward and backward communications are delayed by the functions of time varying delay $T_m(t)$ and $T_s(t)$ as follows

Assumption 3: $T_m(t)$, $T_s(t)$ are continuously differentiable functions and satisfy as follows

$$0 \leq T_i(t) < \infty, \quad |\dot{T}_i(t)| < 1, \quad |\ddot{T}_i(t)| < \infty \quad i = m, s$$

where $\dot{T}_i(t)$ are the rate of change of delays. Moreover, $\dot{T}_m(t)$ can be measured at the slave site and $\dot{T}_s(t)$ can be measured at the master side. In [12], the detector of the rate of change delay is proposed.

In addition, for stability analysis as follows we assume that

Assumption 4: All signals belong to $\mathcal{L}_{2e}$, the extended $\mathcal{L}_2$ space.

III. CONTROL OBJECTIVES

In [11], [12], stability condition is restricted by the magnitude of the the communication delay and the damping of the system. So we would like to design the control inputs τ_m and τ_s to achieve as follows

Control objective 1: The teleoperation system with time varying delay is stable in dependent of the magnitude of the communication delay and the damping of the system.

And we would like to design to achieve the minimal level of transparency as follows

Control objective 2: The synchronization of teleoperation is achieved when the communication delays are constant and the slave is allowed to move freely.

Control objective 3: The static contact force in slave side is accurately transmitted to the human operator in the master side with $\ddot{q}_i = \dot{q}_i = 0$ when the communication delays are constant.

IV. CONTROL DESIGN

In order to achieve the delay-independent stability for teleoperation system, we design the master and slave robot controller.

A. Feedback Passivation

The master and slave robot inputs are given as,

$$\begin{cases} \tau_m(t) = -M_m\Lambda\dot{q}_m(t) - C_m\Lambda q_m(t) + B_m q_m + F_m(t) \\ \tau_s(t) = -M_s\Lambda\dot{q}_s(t) - C_m\Lambda q_s(t) + B_s q_s + F_s(t) \end{cases} \tag{6}$$

where $\Lambda = \mathrm{diag}(\lambda_1, \cdots, \lambda_n) \in \mathcal{R}^{n\times n}$ is a positive definite diagonal control gain matrix and F_m and F_s are the additional inputs required for synchronized control in the next section. Substituting (6) into (1), the master and slave robots dynamics are represented as

$$\begin{cases} M_m\dot{r}_m(t) + C_m r_m(t) = F_{op} + F_m \\ M_s\dot{r}_s(t) + C_s r_s(t) = -F_{env} + F_s \end{cases} \tag{7}$$

where the vectors r_m and r_s are the new outputs of the master and slave robots. They are defined by linear combinations of the joint angle and the joint velocity vectors as

$$\begin{cases} r_m = \dot{q}_m + \Lambda q_m \\ r_s = \dot{q}_s + \Lambda q_s \end{cases} \tag{8}$$

Then we have the following lemma.

Lemma 1: Consider the systems described by (7). We define the inputs of master and slave robot dynamics as $F_m' = F_m + F_{op}$ and $F_s' = F_s - F_{env}$ and the outputs as r_m and r_s respectively. Then, the systems with the above inputs and outputs are passive if there is a constant β such that

$$\int_0^t r_i^T(\xi) F_i'(\xi) d\xi \geq -\beta \qquad i = m, s. \tag{9}$$

Proof: Proof is straightforward. See [14]. ■

Thus, using feedback passivation as (6), the master and slave robot dynamics are passive with respect to the new outputs (8) which contain both the joint angle and velocity vectors. The teleoperation, therefore, can be controlled in the passivity framework for the joint angle and velocity signals by new output.

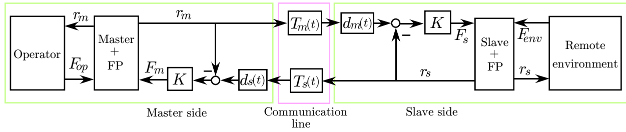

Fig. 1. Teleoperation System

B. Synchronized Control Law Considering Time Varying Communication Delays

We propose the following synchronized control low considering time varying delay,

$$\begin{cases} F_m(t) = K\{d_s(t)r_s(t-T_s(t)) - r_m(t)\} \\ F_s(t) = K\{d_m(t)r_m(t-T_m(t)) - r_s(t)\} \end{cases} \tag{10}$$

where $K \in \mathcal{R}^{n\times n}$ is a positive definite diagonal control gain matrix and $d_m(t)$, $d_s(t) \in \mathcal{R}^{n\times n}$ are positive diagonal time varying gain matrices depending on $\dot{T}_m(t)$ and $\dot{T}_s(t)$ as follow

$$\begin{cases} d_m(t) = \sqrt{1-\dot{T}_m(t)} \cdot I \\ d_s(t) = \sqrt{1-\dot{T}_s(t)} \cdot I \end{cases} \tag{11}$$

where $I \in \mathcal{R}^{n\times n}$ is unit matrix. The proposed synchronized control low considering time varying delay is shown in Fig. 1. Substituting (10) into (7), the closed loop systems can be described as

$$\begin{cases} M_m\dot{r}_m + C_m r_m = F_{op} + K\{d_s(t)r_s(t-T_s(t)) - r_m\} \\ M_s\dot{r}_s + C_s r_s = -F_{env} + K\{d_m(t)r_m(t-T_m(t)) - r_s\} \end{cases} \tag{12}$$

V. STABILITY ANALYSIS

In this section, we analyze the proposed synchronized control law considering time varying communication delays.

Theorem 1: Consider the system described by (12). Then, under *Assumptions 1-4*, the teleoperation system is delay-independent stable and the new outputs of master and slave robots via time varying gains error are asymptotically stable. This theorem shows that *Control objective 1* is achieved.

Proof: Define a function for the system with respect to state vector $x(t) = [r_m^T(t) \;\; r_s^T(t)]^T$ as

$$\begin{aligned} V(x,t) =& r_m^T(t)M_m r_m(t) + r_s^T(t)M_s r_s(t) \\ &+ \int_{t-T_m(t)}^{t} r_m^T(\xi)Kr_m(\xi)d\xi + \int_{t-T_s(t)}^{t} r_s^T(\xi)Kr_s(\xi)d\xi \\ &+2\int_0^t \left\{F_{env}^T(\xi)r_s(\xi)\right\}d\xi + 2\int_0^t \left\{-F_{op}^T(\xi)r_m(\xi)\right\}d\xi \end{aligned} \tag{13}$$

First, we prove that the function V is positive semi-definite. In (13), M_m and M_s are positive definite (by *Property 1*), K is positive semi-definite and the operator and the environment are passive (by *Assumption 1*). Thus, the function V is positive semi-definite. The derivative of this function V along solution trajectories of the system with the *Property 2* is given by

$$\begin{aligned} \dot{V} =& 2d_s(t)r_m^T Kr_s(t-T_s(t)) - 2r_m^T Kr_m \\ &+2d_m(t)r_s^T Kr_m(t-T_m(t)) - 2r_s^T Kr_s \\ &+r_m^T Kr_m - \left(1-\dot{T}_m(t)\right) r_m^T(t-T_m(t))Kr_m(t-T_m(t)) \\ &+r_s^T Kr_s - \left(1-\dot{T}_s(t)\right) r_s^T(t-T_s(t))Kr_s(t-T_s(t)). \end{aligned} \tag{14}$$

Substituting (11) into (14), we can get

$$\begin{aligned} \dot{V} =& 2\sqrt{1-\dot{T}_s(t)}r_m^T Kr_s(t-T_s(t)) - 2r_m^T Kr_m \\ &+2\sqrt{1-\dot{T}_m(t)}r_s^T Kr_m(t-T_m(t)) - 2r_s^T Kr_s \\ &+r_m^T Kr_m - \left(1-\dot{T}_m(t)\right)r_m^T(t-T_m(t))Kr_m(t-T_m(t)) \\ &+r_s^T Kr_s - \left(1-\dot{T}_s(t)\right)r_s^T(t-T_s(t))Kr_s(t-T_s(t)). \end{aligned} \tag{15}$$

The above equation is easily transformed into the following equation

$$\begin{aligned} \dot{V} =& -\{r_m - d_s(t)r_s(t-T_s(t))\}^T K\{r_m - d_s(t)r_s(t-T_s(t))\} \\ &-\{r_s - d_m(t)r_m(t-T_m(t))\}^T K\{r_s - d_m(t)r_m(t-T_m(t))\}. \end{aligned} \tag{16}$$

Thus, the derivative of the Lyapunov function $\dot{V}$ is negative semi-definite. Since V is lower-bounded by zero and $\dot{V}$ is negative semi-definite, we can conclude that the signals r_m, r_s are bounded by using Lyapunov theory. Moreover (16) shows $r_m(t) - d_s(t)r_s(t-T_s(t))$ and $r_s(t) - d_m(t)r_m(t-T_m(t)) \in \mathcal{L}_2$. Note that Laplace transform of (8) yields strictly proper, expotentially stable, transfer functions between r_m, r_s and q_m, q_s are given as

$$Q_i(\mathrm{s}) = \begin{bmatrix} \frac{1}{\mathrm{s}+\lambda_1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \frac{1}{\mathrm{s}+\lambda_n} \end{bmatrix} R_i(\mathrm{s}) \tag{17}$$

where "s" is the Laplace variable, the $R_i(\mathrm{s})$ and $Q_i(\mathrm{s})$ are the Laplace transform of the r_i and q_i respectively. Since r_m, $r_s \in \mathcal{L}_\infty$ and (17), the outputs of system will have the property $\dot{q}_m$, q_m, $\dot{q}_s$ and $q_s \in \mathcal{L}_\infty$. Consequently, the teleoperation system is delay-independent stable.

Furthermore, we show that the new outputs of master and slave robots via time varying gains errors are asymptotically stable. From *Assumption 2*, the operational and environmental force are bounded by the function of the r_m, r_s as F_{op}, F_{env}. From (10), it is easy to see that F_m, $F_s \in \mathcal{L}_\infty$. Then, we can get that τ_m, $\tau_s \in \mathcal{L}_\infty$. From (1), *Property 1* and *3*, the master and slave robot accelerations are bounded as $\ddot{q}_m$, $\ddot{q}_s \in \mathcal{L}_\infty$. They show $\dot{r}_m$, $\dot{r}_s \in \mathcal{L}_\infty$. The derivative of

$r_m(t) - d_s(t)r_s(t - T_s(t))$ is given by

$$\frac{d}{dt}\left\{r_m(t) - \sqrt{1 - \dot{T}_s(t)}r_s(t - T_s(t))\right\}$$
$$= \dot{r}_m(t) - \frac{1}{2}\left(1 - \dot{T}_s(t)\right)^{-\frac{1}{2}}\left(-\ddot{T}_s(t)\right)r_s(t - T_s(t))$$
$$- \left(1 - \dot{T}_s(t)\right)^{\frac{3}{2}}\dot{r}_s(t - T_s(t)) \quad (18)$$

Using *Assumption 3* and r_i, $\dot{r}_i \in \mathcal{L}_\infty$, the above equation $\frac{d}{dt}\{r_m(t) - d_s(t)r_s(t - T_s(t))\} \in \mathcal{L}_\infty$. Similarly, $\frac{d}{dt}\{r_s(t) - d_m(t)r_m(t - T_m(t))\} \in \mathcal{L}_\infty$. This implies that the new outputs of master and slave robots via time varying gains errors are asymptotically stable as follow

$$\lim_{t\to\infty}\{r_m(t) - d_s(t)r_s(t - T_s(t))\}$$
$$= \lim_{t\to\infty}\{r_s(t) - d_m(t)r_m(t - T_m(t))\} = 0 \quad (19)$$

(see [15]). ■

In our proposed control strategy, although the teleoperation system is delay-independent stable, the position coordination can not be achieved under time varying delay. But if communication delay is constant, our proposed control structure is equivalent to reference [13]. In this case, therefore, the position coordination and the static force reflection are achieved (see [7], [13]). This means that *Control objective 2* and *Control objective 3* are achieved. So our proposed method append delay-independent stability under time varying delay to the control method in [13].

Remark 1: In our proposed method, not only velocity signals but also position signals are scaled by the time varying gains unlike [12]. So, when the delayed change is several times, it is insufficient for the performance of the force reflection and the master-slave position coordination. In our proposed method, however, stability condition is independent of the magnitude of the communication delay and the damping of the system. So, unlike references [11], [12], the gains of our proposed control law can be selected at the appropriate values and stability of our proposed teleoperation system is guaranteed for unpredictable delay increase.

VI. EVALUATION BY CONTROL EXPERIMENTS

In this section, we verify the efficiency of the proposed teleoperation methodology. The experiments were carried out on a pair of identical direct-drive planar 2 links revolute-joint robot as shown in Fig. 2. The inertia matrices and the Coriolis matrices are identified

$$M_m = M_s = \begin{bmatrix} \theta_1 + 2\theta_3\cos(q_2) & \theta_2 + \theta_3\cos(q_2) \\ \theta_2 + \theta_3\cos(q_2) & \theta_2 \end{bmatrix}$$
$$C_m = C_s = \begin{bmatrix} -\theta_3\sin(q_2)\dot{q}_2 & -\theta_3\sin(q_2)(\dot{q}_1 + \dot{q}_2) \\ \theta_3\sin(q_2)\dot{q}_1 & 0 \end{bmatrix}$$

$\theta_1 = 0.366[\text{kgm}^2], \theta_2 = -0.0291[\text{kgm}^2], \theta_3 = 0.0227[\text{kgm}^2]$

A remote environment is using a hard aluminium wall covered by a rubber on the slave side as shown in Fig. 3. We also measure the operational and the environmental torque using the force sensors. For implementation of the controllers and communication line, we use a dSPACE system (dSPACE Inc.) and 2.5 [ms] sampling rate is obtained.

Fig. 2. Experimental setup

Fig. 3. Remote environment and slave

To show the relationship between the magnitude of the communication delay and the performance, the experiments have been carried out with two versions of artificial time varying communicaition delays as

- Small time delays shown as Fig. 4
- Large time delays shown as Fig. 5

In normal times, the magnitude of the small time delays are 0.2 [s] and the magnitude of the large time delays are 0.7 [s]. But we consider unpredictable delay increase caused by using the internet as a communication line, the time delays increase temporarily 0.3 [s] in about 9-15 [s] and 18-24 [s]. Under these conditions, the time varying gains $d_m(t)$ and $d_s(t)$ are shown as Fig. 6.

The controller parameters K and Λ are selected as

$$K = \begin{bmatrix} 2.5 & 0 \\ 0 & 1.3 \end{bmatrix}, \quad \Lambda = \begin{bmatrix} 5.7 & 0 \\ 0 & 4 \end{bmatrix} \quad (20)$$

Two kind of experimental conditions are given as follow

- Case 1: The slave moves without any contact.
- Case 2: The slave moves in contact with environment.

Fig. 7 shows the results of Case 1 with small time varying delays and Fig. 9 shows the results of Case 1 with large time varying delays. They exemplify time responses of joint angle and operational torque signals. These figures illustrate that the proposed teleoperation is delay-independent stable and when the communication delay increase severely,

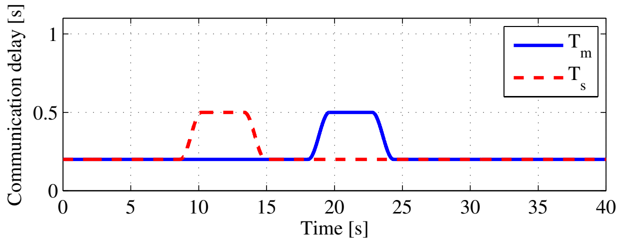

Fig. 4. Small time delays

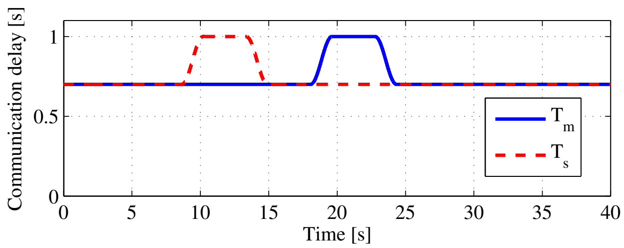

Fig. 5. Large time delays

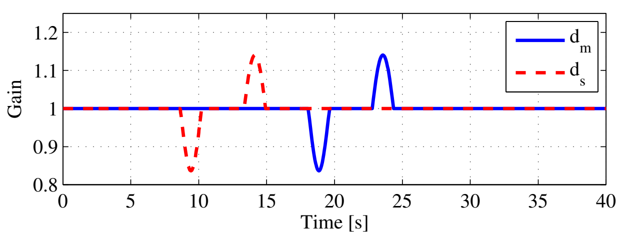

Fig. 6. Time varying gains

the teleoperation is stable. Moreover, The joint angles of the slave virtually track the joint angles of the master. Because when the communication delay is constant, the master-slave position coordination is achieved. On the other hand, comparing Fig. 7 with Fig. 9, it is explicit that the operational torque is bigger in case of the large time delays. This means operational performance degradation in case of the large time delays. So, our proposed method guarantees that the teleoperation is delay-independent stable, but the operational performance depends heavily on the magnitude of the communication delays.

Fig. 8 shows the results of Case 2 with small time varying delays and Fig. 10 shows the results of Case 2 with large time varying delays. They illustrate time resoponses of joint angle signals and operational, environmental torque signals. These figures demonstrate when the slave robot is contacting the environment, the proposed teleoperation is stable and the contact force is almost reflected to the operator. So the operator can perceive the environment through the torque reflection. Because when the communication delay is constant, the static force reflection is achieved.

VII. CONCLUSIONS

In this paper, we proposed the control strategy for nonlinear teleoperation system with time varying communication delay. The proposed method was a novel passivity based controller that introduces the time varying gains [10], [11] to the conventinal passivity based controller [7], [13]. In the proposed control strategy, the stability condition was independent of the magnitude of the communication delay and the damping of system. So we could design control parameters appropriately. Using Lyapunov stability methods, the delay-independent stability of origin was shown. Finally, several experimental results showed the effectiveness of our proposed framework.

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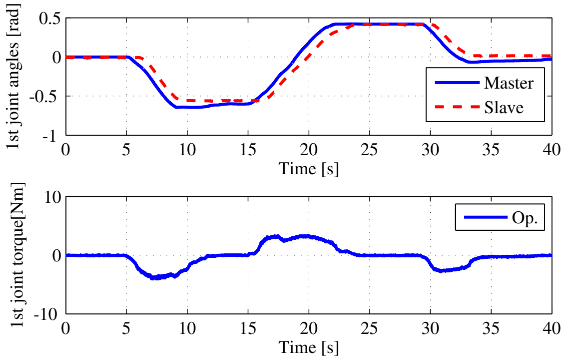
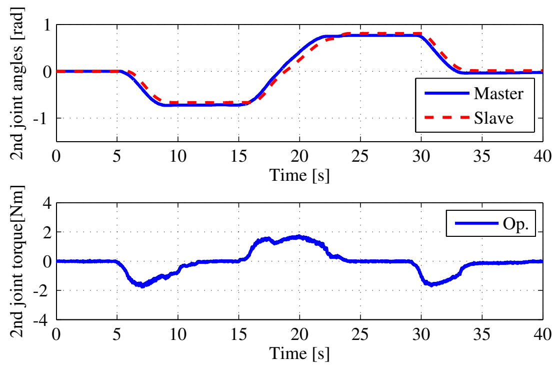
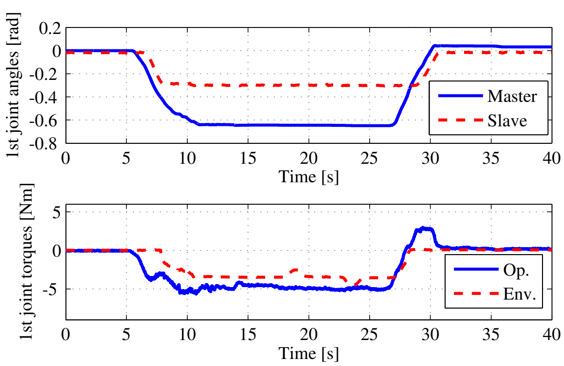


(a) 1st joint

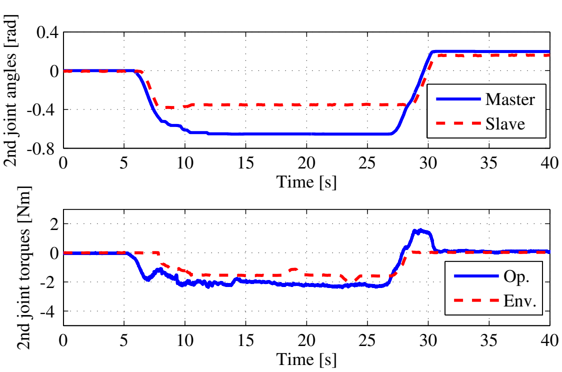


(b) 2nd joint

Fig. 7. Time responses in Case 1 (small time delays)

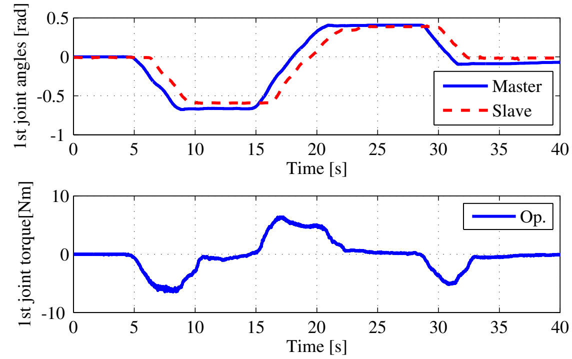


(a) 1st joint

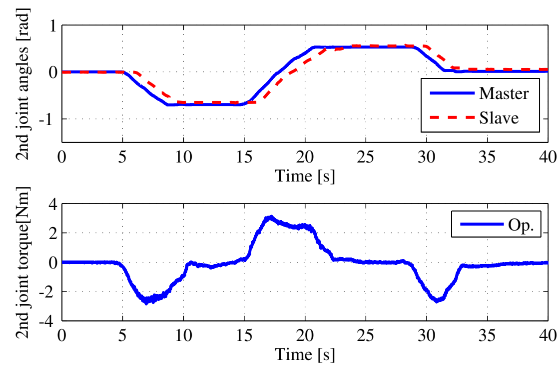


(b) 2nd joint

Fig. 8. Time responses in Case 2 (small time delays)

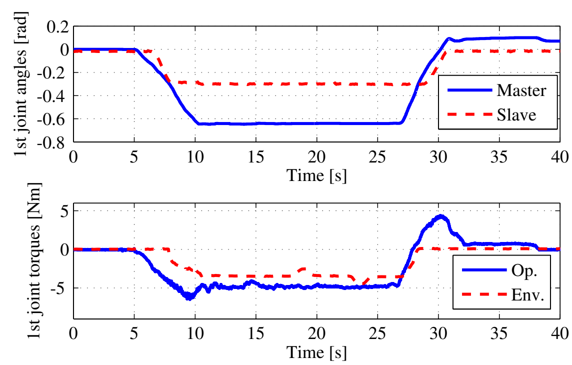


(a) 1st joint

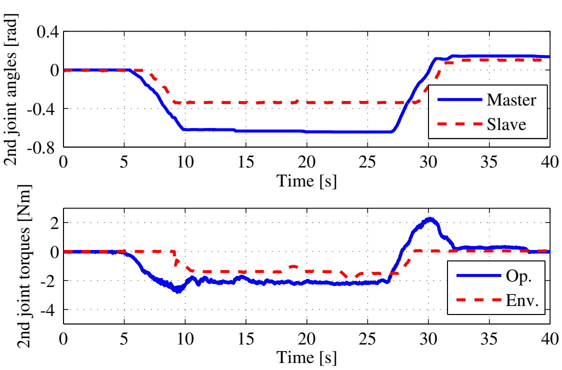


(b) 2nd joint

Fig. 9. Time responses in Case 1 (large time delays)



(a) 1st joint



(b) 2nd joint

Fig. 10. Time responses in Case 2 (large time delays)