Passivity Based Control of Bilateral Teleoperators with Time Delay using Low-Pass Filters

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Abstract: Bilateral teleoperators, designed within the passivity framework using the concepts of scattering transformation and two port network theory, provide robust stability in the constant delay condition in a network. In this paper, we propose a new coordination architecture for bilateral teleoperation in which static feedback gains in the master and slave robots are replaced by dynamic feedbacks using nonlinear low-pass filters. This architecture can select low-frequency gain and high-frequency gain independently. We can select the cut-off frequencies of the master block and slave block independently. We show the stability of our system and the ultimate boundedness of the position error between the master manipulator and the slave manipulator trajectories using a Lyapunov Krasovskii functional, in free motion with transmission time delay. This architecture guarantees accurate position tracking of the two robots in free motion with transmission time delay. Simulation results are presented that demonstrate the effectiveness of the proposed architecture for position and force tracking control.

Keywords: Teleoperation; Passivity; Scattering transformation; Time delay; Tracking

1. INTRODUCTION

A bilateral teleoperator system is a dual robot control system that synchronizes the motion of a master robot and a remote slave robot, where the master robot is controlled by a human operator. This system consists of the master and remote slave robot manipulators connected via a communication network block; the human operator can manipulate the slave robot safely from a long distance. For better performance of delicate tasks, accurate information regarding the remote environment must be conveyed to the human operator. Bilateral teleoperators can allow the operator to feel the environment force accurately. The bilateral teleoperation is applied to practical problems in various areas such as operations in hazardous environments, undersea exploration, space development, and robotic surgery.

In a bilateral teleoperator system, in addition to stabilization of the system, the following are primary design goals: (1) the remote slave manipulator robot should be able to accurately track the position of the master manipulator robot, and (2) when the remote slave manipulator contacts the remote environment, the slave robot should transmit accurate information regarding the acting forces to the human operator via the master robot.

One impediment to the implementation of the bilateral teleoperator is the existence of time delay. Time delay in data transmission between the master and slave sites may cause various problems. In particular, in a closed loop system, time delay can destabilize an originally stable system. The instability in force reflecting teleoperation has been a critical problem in the research field of bilateral teleoperators for a long time.

This problem was solved by Anderson and Spong (1989). Their method uses network theory; the communication block is passified from force to velocity by scattering transformations. This architecture guarantees the stability of the bilateral teleoperators, independent of a constant delay. Niemeyer and Slotine (1991) extended these results by adding the concept of wave-variables. A bilateral teleoperation architecture with scattering transformation and wave-variables is shown in Fig. 1. Kim (1992) showed that the bilateral control method using wave-variables guarantees robust stability of the teleoperator; however, the method had a sluggish response at high delays. The above discussed methods provide velocity synchronization between the master manipulator and the remote slave manipulator; thus, steady-state position errors remain between the two manipulators when initial position errors
exist. Chopa and Spong (2004) solved this problem by defining new outputs that consist of manipulator positions and velocities, and showed the passivities of the master and slave blocks from the input forces to the new outputs. Adaptive control schemes were also introduced by Chopa and Spong (2004); Chopra et al. (2008). Nuro et al. (2010) extended this method to the case with gravity.

However, in these architectures, steady-state position errors remain when Coulomb and viscous frictions exist in the two manipulators. We must increase gains to reduce the steady-state position error; however, high gain causes an different problem: a trade-off exists between the prevention of nonsmooth behavior and the steady-state position accuracy.

In this paper, we propose a new coordination architecture for bilateral teleoperation that does not include any adaptive mechanism. Our architecture can design high-frequency gain and low-frequency gain separately; it relaxes the above trade-off issue. We prove the ultimate boundedness of the master manipulator and the remote slave manipulator trajectories in the proposed control architecture using the Lyapunov method and demonstrate the position synchronization of the master-slave manipulator using simulations.

2. PROBLEM DEFINITION

We review the Lagrangian dynamics of a general robotic system. Assuming the absence of disturbances, the Euler-Lagrange equations of motions for the n-link master manipulator and the n-link slave manipulator are given by

\[ M_m(q_m) \ddot{q}_m + C_m(q_m, \dot{q}_m) \dot{q}_m + g_m(q_m) = F_h + \tau_m \]

\[ M_s(q_s) \ddot{q}_s + C_s(q_s, \dot{q}_s) \dot{q}_s + g_s(q_s) = \tau_s - F_e, \]

where \( q_m, q_s \) denote n-vectors of joint displacements; \( \dot{q}_m, \dot{q}_s \) the n-vectors of joint velocities; \( \tau_m, \tau_s \) the n-vectors of applied torques; \( M_m(q_m), M_s(q_s) \) symmetric positive definite matrices of centripetal and Coriolis torques; and \( g_m(q_m), g_s(q_s) \) n-vectors of gravitational torques. The above equations of motion are nonlinear and interconnected, they exhibit certain fundamental properties because of their Lagrangian dynamic structure.

**Property 1** The inertia matrices \( M_m(q_m), M_s(q_s) \) are symmetric positive definite, and bounded. Moreover, there exist positive constants \( m_{m1}, m_{m2}, m_{s1}, \) and \( m_{s2} \) such that

\[ m_{m1} I < M_m(q_m) < m_{m2} I \]

\[ m_{s1} I < M_s(q_s) < m_{s2} I. \]

**Property 2** The matrices \( \dot{M}_m(q_m) - 2C_m(q_m, \dot{q}_m) \) and \( M_s(q_s) - 2C_s(q_s, \dot{q}_s) \) are skew-symmetric, which leads to

\[ x^T (\dot{M}_m(q_m) - 2C_m(q_m, \dot{q}_m)) x = 0 \]

\[ x^T (M_s(q_s) - 2C_s(q_s, \dot{q}_s)) x = 0 \]

\[ \dot{M}_m(q_m) - C_m(q_m, \dot{q}_m) - C_m^T(q_m, \dot{q}_m) = 0 \]

\[ M_s(q_s) - C_s(q_s, \dot{q}_s) - C_s^T(q_s, \dot{q}_s) = 0. \]

We define coordination errors between the master manipulator position and the slave manipulator position as

\[ e_m(t) = q_m(t - T) - q_m(t) \]

\[ e_s(t) = q_s(t - T) - q_s(t), \]

where \( T \) denotes the transmission delay. In this paper, we propose a new coordination architecture for bilateral teleoperation. The final goals of our research are listed below:

(1) To show the ultimate boundedness of the master manipulator and the remote slave manipulator trajectories using a Lyapunov method in the free motion case and the case where the environmental force and the command force are added to the system with transmission time delay.

(2) To demonstrate the position and force synchronization of the master manipulator and the remote slave manipulator in free motion with transmission time delay, i.e.,

\[ \lim_{t \to \infty} e_m(t) = \lim_{t \to \infty} e_s(t) = 0 \]

(3) To demonstrate the position and force synchronization when Coulomb and viscous frictions exist in the remote slave manipulator.

In this paper, we treat only the free motion case; research into the case with exogenous forces will be the object of future work. Moreover, in this paper, the practical synchronization property under frictions is only shown via simulations; its mathematical proof requires further research.

3. THE PREVIOUS BILATERAL TELEOPERATION ARCHITECTURE OF SCATTERING TRANSFORMATION

In this section, we introduce the previously proposed bilateral teleoperation architecture using scattering transformation developed by Chopa and Spong (2004). This architecture is an improvement over the traditional teleoperator architecture Anderson and Spong (1989); Niemeyer and Slotine (1991) of Fig. 1. The teleoperator consists of the following subsystems: the human operator, the master block, the communication block, the slave block, and the environment.

The human operator controls the master manipulator with force \( F_h \), and the master manipulator outputs velocity \( \dot{q}_m \). To allow position synchronization, new outputs \( r_m, r_s \) of the bilateral teleoperator are defined based on \( \dot{q}_m, q_m, \dot{q}_s, q_s, \) and \( \Lambda \), as

\[ r_m = \dot{q}_m + \Lambda q_m \]

\[ r_s = \dot{q}_s + \Lambda q_s, \]

where \( r_m, r_s \) are n-vectors of the new outputs of the subsystems, and \( \Lambda \) is a constant, positive-definite, diagonal matrix. The new output \( r_m \) is transmitted to the remote slave manipulator via the communication block. Thereafter, time delay \( T \) is incurred in transmission of data on the communication block. On the slave side, if the slave manipulator contacts the remote environment, the remote slave manipulator adds force \( F_e \) and moves with velocity \( \dot{q}_s \).
We choose the master manipulator and the slave manipulator inputs as
\[
\tau_m = \bar{\tau}_m - M_m(q_m)\Lambda \bar{q}_m - C_m(q_m, \dot{q}_m)\Lambda \dot{q}_m + g_m(q_m),
\]
\[
\tau_s = \bar{\tau}_s - M_m(q_s)\Lambda \bar{q}_s - C_m(q_s, \dot{q}_s)\Lambda \dot{q}_s + g_m(q_s),
\]
where \(\bar{\tau}_m, \bar{\tau}_s\) are \(n\)-vectors of the coordinate torques. In this paper, we assume that the physical parameters of the master manipulator and the slave manipulator are known. From (1), (7), and (8), the master manipulator and the slave manipulator dynamics are given by
\[
M_m(q_m)\ddot{r}_m + C_m(q_m, \dot{q}_m)\dot{r}_m = \bar{\tau}_m
\]
\[
= -F_{md}
\]
\[
M_s(q_s)\ddot{r}_s + C_s(q_s, \dot{q}_s)\dot{r}_s = \bar{\tau}_s
\]
\[
= F_{sd}.
\]

The standard bilateral teleoperation architecture with scattering transformation (Chopa and Spong, 2004) is shown in Fig. 2. In this architecture, the master block and the slave block are passive from force \(F_b, F_s\) to velocity \(\dot{q}_m, \dot{q}_s\), respectively. The communication block is not originally passive as it is independent of the constant time delay in the network; however, it is passified by the scattering transformations,
\[
u_m = \frac{1}{\sqrt{2b}}(F_{md} + br_{md})
\]
\[
u_m = \frac{1}{\sqrt{2b}}(F_{md} - br_{md})
\]
\[
u_s = \frac{1}{\sqrt{2b}}(F_{sd} + br_{sd})
\]
\[
u_s = \frac{1}{\sqrt{2b}}(F_{sd} - br_{sd}),
\]
where \(u_m, v_m, u_s,\) and \(v_s\) are \(n\)-vectors of the outputs of the scattering transformation block. \(b\) is the \(n \times n\) symmetric, positive-constant, definite matrix of the characteristic wave-impedance, and \(r_{md}, r_{sd}\) are \(n\)-vectors of the signals derived from the scattering transformation. \(F_{md}, F_{sd}\) are \(n\)-vectors indicating coordination torques, which are given by
\[
F_{md} = K_m(r_{md} - r_m)
\]
\[
F_{sd} = K_s(r_{sd} - r_s),
\]
where \(K_m\) and \(K_s\) are proportional gains. To synchronize the position and velocity between the master and the slave, we choose the gains as
\[
K_m = K_s = 2b,
\]
and by (10), (11), (12), and (13), the resulting transmission equations are obtained as
\[
r_{md}(t) = \frac{1}{2}(r_m(t - T) + r_s(t))
\]
\[
r_{sd}(t) = \frac{1}{2}(r_s(t - T) + r_m(t)),
\]
which is free from wave-reflections. From (12) and (14), the coordination torques \(F_{md}\) and \(F_{sd}\) are given by
\[
F_{md} = \frac{b}{2}(r_s(t - T) - r_m)
\]
\[
F_{sd} = \frac{b}{2}(r_m(t - T) - r_s).
\]

These coordination torques \(F_{md}\) and \(F_{sd}\) synchronize the position and velocity between the master robot and the slave robot, respectively; however, when the manipulating force by human \(F_b\) and the environmental force \(F_s\) are added to the master manipulator and the slave manipulator, respectively, the steady-state position errors between the two manipulator are likely to become non-zero.

4. THE NEW COORDINATION ARCHITECTURE

In this section we propose a new coordination architecture for bilateral teleoperation.

4.1 The New Feedback Control Law

In this section, we introduce a new feedback control law for the bilateral teleoperator.

The new coordination torques \(\bar{\tau}_m, \bar{\tau}_s\) are given by
\[
\bar{\tau}_m(t) = K_p(r_s(t - T) - r_m(t)) + K_{im}(q_m)\dot{S}_m(t)
\]
\[
\bar{\tau}_s(t) = K_p(r_m(t - T) - r_s(t)) + K_{is}(q_s)\dot{S}_s(t),
\]
where \(K_p\) is an \(n \times n\) symmetric, positive-definite matrix; and \(K_{im}, K_{is}\) are \(n \times n\) symmetric positive definite matrices. \(K_p\) indicates the proportional gain. \(K_{im}, K_{is}\) are the gains for the filtered signal. \(\dot{S}_m(t)\) and \(\dot{S}_s(t)\) are the state variables of filters driven by \(r_s(t - T) - r_m(t)\) and \(r_m(t - T) - r_s(t)\), respectively. The filter dynamics are given by
\[
M_m(q_m)\dot{S}_m(t) = -(C_m(q_m, \dot{q}_m) + K_{im}(q_m))\dot{S}_m(t)
\]
\[
+ \beta K_p(r_s(t - T) - r_m(t))
\]
\[
M_s(q_s)\dot{S}_s(t) = -(C_s(q_s, \dot{q}_s) + K_{is}(q_s))\dot{S}_s(t)
\]
\[
+ \beta K_p(r_m(t - T) - r_s(t)),
\]
where \(\beta\) is a positive constant parameter. The new coordination architecture for bilateral teleoperation is shown in Figs.3, 4, and 5. The new coordination architecture has an advantage over the previous architecture of scattering transformation (Chopa and Spong, 2004) as described below. In the bilateral teleoperator, the high-frequency gain is originally ineffective in terms of position tracking because of the existence of transmission delay. In addition, a high-gain feedback in the high-frequency domain might cause undesirable behavior. On the other hand, maintaining a high low-frequency gain is useful for the improvement of the tracking accuracy. In particular, this kind of gain can reduce the tracking offset caused by Coulomb frictions. The proposed method can design the high-frequency gain.
Fig. 4. The Proposed Master Block

and the low-frequency gain separately. Therefore, the high-
frequency gain can be set low, and the low-frequency
gain can be set high, whereas in the standard scattering
transformation architecture, the feedback gains are flat in
the frequency domain.

To show the characteristics of the proposed controller
mentioned above, we consider the properties of (8) and (9)
for simple cases. Assume that \( M_m, M_s \) are constant
matrices, \( C_m, C_s \) are zero, and \( K_{qm} = (1/a)M_m, K_{qs} =
(1/a)M_s (a > 0) \). Then, (8) and (9) have linear
dynamics. The transfer function matrices \( G_m(s) \) from \( r_m(t - T) - r_m \)
to \( \tau_m \), and \( G_s(s) \) from \( r_m(t - T) - r_s \) to \( \tau_s \) are
\[
G_m(s) = G_s(s) = \left(1 + \frac{\beta}{as + 1}\right)K_p.\tag{18}
\]

In these transfer function matrices, the high-frequency
 gains are \( K_p \), the low-frequency gains are \( (1 + \beta)K_p \),
and the cut-off frequencies are \( 1/a \). Consequently, by changing
the value of \( \beta \), we can choose the low-frequency gain
relative to the high-frequency gain \( K_p \). In this case, (8)
represents linear low-pass filters. Therefore, for general
nonlinear cases, the filters (9) have low-pass filter
properties as well.

### 4.2 Stability Analysis

In this section, we consider a nonlinear bilateral teleop-
eration system in free motion \( (F_\text{h}(t) = F_\text{s}(t) = 0) \). The
physical parameters of the master manipulator and the
slave manipulator are known. In the initial conditions, all
signals are assumed to be bounded.

**Theorem 1.** Assume that \( K_pA + \Lambda K_p > 0, 0 < \beta < 1, \)
\( F_\text{h} = 0 \), and \( F_\text{s} = 0 \). Then, the position tracking errors
\( e_m, e_s \) and the velocity tracking errors \( \dot{e}_m, \dot{e}_s \) converge
to zero as \( t \to \infty \). Moreover, the master and the slave
manipulator trajectories are ultimately bounded.

**Proof:** We define a Lyapunov-Krasovskii functional \( V \) as
\[
V = z_m^T(t)\Phi_m(q_m)z_m(t) + z_s^T(t)\Phi_s(q_s)z_s(t)
+ e_m^T(t)K_m e_m(t) + e_s^T(t)K_s e_s(t)
+ (1 + \beta) \int_{-T}^{0} (r_m^T(s)K_p r_m(s) + r_s^T(s)K_p r_s(s))\,ds
\geq 0,
\]
\[
z_m^T(t) = [r_m(t) S_m(t)] z_s^T(t) = [r_s(t) S_s(t)]
\]
\[
\Phi_m(q_m) = \begin{bmatrix} M_m(q_m) M_m(q_m) \\ M_m(q_m) p M_m(q_m) \end{bmatrix}
\]
\[
\Phi_s(q_s) = \begin{bmatrix} M_s(q_s) M_s(q_s) \\ M_s(q_s) p M_s(q_s) \end{bmatrix}
\]
where \( K_p \) is the constant \( n \times n \) symmetric, positive-definite
matrix, and \( p \) is a constant positive parameter. To make
the Lyapunov-Krasovskii functional \( V \) a positive
semidefinite storage functional, \( p \) must be larger than 1.

By (9), (16), (17), (19), and (20), the time derivative of
the Lyapunov-Krasovskii functional along the trajectories
is obtained as
\[
\dot{V} = 2r_m^T(-C_m r_m + \tau_m) + r_m^T M_m r_m
+ 2r_s^T(-C_s r_s + \tau_s) + r_s^T M_s r_s
+ 2pS_m^T(C_m + K_{qm}) S_m - \beta K_p (r_s(t - T) - r_m)
+ pS_m^T M_m S_m + 2\beta K_p (r_s(t - T) - r_m)^T r_m
+ 2pS_s^T(C_s + K_{qs}) S_s - \beta K_p (r_m(t - T) - r_s)
+ pS_s^T M_s S_s + 2\beta K_p (r_m(t - T) - r_s)^T r_s
+ 2r_m^T(C_m + K_{qm}) S_m + 2\dot{r}_m^T K_p e_m
+ 2S_m^T M_m r_m + 2S_m^T(-C_m r_m + \tau_m)
+ 2r_s^T(C_s + K_{qs}) S_s + 2\dot{r}_s^T K_p e_s
+ 2S_s^T M_s r_s + 2S_s^T(-C_s r_s + \tau_s)
+ (1 + \beta) r_m^T K_p r_m + (1 + \beta) r_s^T K_p r_s
- (1 + \beta) r_m^T (t - T) K_p r_m(t - T)
- (1 + \beta) r_s^T (t - T) K_p r_s(t - T).
\]

Using (3), (4), and (16), the derivative can reduced to
\[
\dot{V} = -2(p-1)S_m^T K_{qm} S_m
+ (2p-1)S_m^T K_p r_m
+ (2p-1)\dot{r}_m^T (t - T) K_p S_m
- 2(p-1)S_s^T K_{qs} S_s
+ 2p-1S_s^T K_p r_s
+ 2p-1\dot{r}_s^T (t - T) K_p S_s
- (1 + \beta)(r_s(t - T) - r_m)^T K_p (r_s(t - T) - r_m)
- (1 + \beta)(r_m(t - T) - r_s)^T K_p (r_m(t - T) - r_s)
+ 2\dot{e}_m^T K_p e_m + 2\dot{e}_s^T K_p e_s.
\]

As \( 0 < \beta < 1 \), we can choose \( p = 1/\beta \) \((> 1)\), which changes
\( \dot{V} \) into the following, simple form:

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Table 1. Common Parameters in the Simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Master</th>
<th>Slave</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass of 1-link (kg)</td>
<td>2.0</td>
<td>4.0</td>
</tr>
<tr>
<td>mass of 2-link (kg)</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>length of 1-link (m)</td>
<td>2.0</td>
<td>4.0</td>
</tr>
<tr>
<td>length of 2-link (m)</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Time Delay(s)</td>
<td>0.4</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Friction Parameters in the Simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Master</th>
<th>Slave</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coulomb friction (Nm)</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>viscous friction (Nm/s)</td>
<td>6.0</td>
<td>12.0</td>
</tr>
</tbody>
</table>

\[ \dot{V} = -2(p - 1)S_m^T K_{im} S_m - 2(p - 1)S_r^T K_{is} S_r - (1 + \beta)(r_m(t - T) - r_m)^T K_p (r_m(t - T) - r_m) - (1 + \beta)(r_m(t - T) - r_s)^T K_p (r_m(t - T) - r_s) + 2\epsilon_m^T K_e\dot{e}_m + 2\epsilon_s^T K_e\dot{e}_s. \]

By defining \( A_m = 2(p - 1)K_{im}, A_s = 2(p - 1)K_{is}, \) and \( B = (1 + \beta)K_p \) and choosing \( K_e = \frac{1}{2}(BA + AB) > 0, \) we find

\[ \dot{V} = -S_m^T A_m S_m - S_r^T A_s S_s - \epsilon_m^T B\dot{e}_m - \epsilon_s^T \Lambda^T B\dot{e}_m - \epsilon_s^T \Lambda^T B\dot{e}_s \leq 0. \]

By (19) and (21), we can show that \( r_m, \dot{r}_m, S_m, S_s, e_m \) and \( \dot{e}_m \) are bounded. From ISS property of (7), \( q_m, \dot{q}_m, \dot{q}_s, \dot{e}_s, \dot{e}_m \) and \( \ddot{e}_s \) are bounded. Therefore, the master and slave manipulator position trajectories and velocities are ultimately bounded. From (9), (16), and (17), \( \dot{S}_m, \dot{S}_s, \ddot{r}_m, \ddot{r}_s, T, \) and \( T \) are bounded. As the time derivatives of (7) are obtained as

\[ \dot{r}_m = \dot{q}_m + \dot{\dot{q}}_m + \dot{\dot{e}}_m, \]
\[ \dot{r}_s = \dot{q}_s + \dot{\dot{q}}_s + \dot{\dot{e}}_s, \]
\[ \ddot{r}_m, \ddot{r}_s, \dot{\dot{e}}_m \] and \( \dot{\dot{e}}_s \) are also bounded. From the boundedness of \( S_m, \dot{S}_m, \dot{S}_s, e_m, \ddot{e}_m, \ddot{e}_s, \ddot{e}_m, \) and \( \dot{\dot{e}}_s, \dot{V} \) is uniformly continuous in time. Consequently, using Barbalat’s lemma, we get

\[ \lim_{t \to \infty} \dot{V} = 0. \]

Therefore, \( e_m(t), \dot{e}_m(t), \ddot{e}_m(t), S_m(t), \) and \( S_s(t) \) tend to zero as \( t \) goes to infinity.

5. SIMULATIONS

In this section, we perform simulations of the proposed architecture using a bilateral teleoperator with 2-link manipulators. We assume the robots move in horizontal planes, such that the force due to gravity is zero. We define the masses and lengths of the two manipulators and time delay as shown in Table 1. The simulations were performed under three different conditions.

First, we performed a simulation of the free motion case without friction. The initial position of the slave robot is \((0, 0)^T\) and the initial position error between the master and slave manipulators is \(q_m(0) - q_s(0) = (\pi/4, \pi/4)^T.\) Figure 6 shows the time responses of the joint angles. The joint positions of the slave robot track the master’s position well.

Second, we performed a simulation of the case in which Coulomb and viscous frictions exist in the two robots. As given in Table 2. The initial conditions were the same as those of the first case. Figure 7 shows the time responses of the joint angles of the previous architecture (Chopa and Spong, 2004) for the second case; there is a steady-state errors in the positions. Figures 8 and 9 show the time responses of the joint angles and the filter variables \((S_m, S_s)\), respectively, of the proposed architecture for the second case. The master and slave positions converge on each other as \( t \to \infty.\)

Finally, we perform a simulation of the case in which the master manipulator is controlled by an exogenous force applied to the ends of the two manipulators for \(0.5 \leq t \leq 2.5.\) Coulomb and viscous frictions exist in both manipulators. As seen in Fig. 10, the master manipulator positions coincide with the slave manipulator positions as \( t \to \infty.\) Figure 11 shows the time responses of the filter variables \((S_m, S_s)\) of our architecture.

6. CONCLUSIONS

In this paper, we proposed a new coordination architecture for a bilateral teleoperator. This architecture guarantees the ultimate boundedness of the joint angles and joint velocity of the two manipulators, and that the position errors and velocity errors between the master manipulator and the remote slave manipulator trajectories tend to zero as \( t \) approaches infinity in the free motion condition. The new method can select the low-frequency gain and high-frequency gain independently; the cut-off frequency can
be also be determined freely. We demonstrate the position synchronization between the master manipulator and the remote slave manipulator using simulations. Adding an adaptive mechanism to our method and consideration of a variable time delay are the objectives of future work.

REFERENCES


