Bilateral Control System of Nonlinear Flexible Master-Slave Arms with Random Delay Using Extended Kalman Filter

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1 Introduction

It is considered that robotic teleoperation technologies are useful to provide human skills in distant places. Moreover, when these technologies are introduced into general environment such as offices, houses, and so on, these should be achieved by using existing network such as LAN, WAN and wireless LANs. Recently, the theory of systems with stochastic delay become rather popular to develop the robotic teleoperation technologies. Therefore, it is important that the random delay is modeled as the stochastic process to develop these technologies. The bilateral control system constructed by a master arm, a slave arm and a communication network is regarded as one of teleoperation technologies. States of these arms are interacted with each other through a communication network which causes the random delay. Thus, the bilateral control system is regarded as the feedback system with the network. Since the states becomes noisy due to the random delay, the system becomes instable. Therefore, to control accurately, the effect of the random delay should be reduced.

Many researchers have studied about the state estimation problem for the random delay. Wu et al. and Guo et al. investigated the mean square exponentially stability for the network system with the long random delay and a type of discrete-time system with random delay [1],[2]. Liu et al. studied the model predictive control problem for the networked system which cause the random delay defined as a Markov chain [3]. Schenato researched to design the optimal estimator. This estimator reduced the effect of the random delay and packet loss [4],[5]. However, these studies does not use the randomness for modeling the random delay. Thus, the random delay could not be enough considered to model the random delay.

On the other hand, a lot of researchers have studied the manipulators and the bilateral control system with or without the time delay. Matsuno et al. has proposed the PDS (Proportional, Derivative and Strain) feedback controller to control the flexible beams [6]. Namerikawa investigated a PD control method and a control strategy for the teleoperation systems with time-varying delay [7],[8]. Mori et al. and Hoshino et al. verified the passivity of the bilateral control system of the flexible master-slave manipulators without the time delay [9],[10]. However, these studies does not considered the random delay.

The bilateral control system with the time-varying delay was researched in our previous researches. The stability and the passivity were proven via the Laypunov theorem and the performance of the proposed system was confirmed [11]. Furthermore, the bilateral control system affected by the random delay was also discussed. The novel Kalman filter was designed for the bilateral control system and its performance was verified by the numerical simulation [12]. In [12], the flexible arm was modeled as the linearized system and the Kalman filter was designed to estimate the state values of the linearized flexible arm. In this paper, the mathematical model of the flexible arm is derived as the nonlinear system and the extended Kalman filter is designed to estimate the state values of this arm.

The bilateral control system for the nonlinear flexible master-slave arms with the random delay is investigated in this paper. By means of the Hamilton’s principle, the rigid master arm and the nonlinear flexible slave arm is modeled. Furthermore, the random delay is described as the sum of an average time delay and a white Gaussian noise. An extended Kalman filter is designed to estimate the state signals for reducing the effect of the random delay. The reaction torque for the master arm and the reference signal for the slave arm are generated by the PD- and PDS-controllers. The numerical simulation is demonstrated to verify the performance of the novel extended Kalman filter for the proposed bilateral control system.
2 Modeling of Bilateral Control System

The proposed bilateral control system is constructed by rigid master and nonlinear flexible slave arms. A high-geared servomotor is introduced to drive the nonlinear flexible slave arm. These arms are connected with a communication network which occurs a random delay (see Fig. 1). Mathematical models of these elements are derived to demonstrate numerical simulations.

2.1 Rigid Master Arm

Fig. 2 shows the rigid master arm which consists of an uniform rigid rod and a hub. The inertial Cartesian coordinate system defines as $O_mX_mY_m$. The mass and the length of this arm is $m_m$ and $\ell_m$. $\tau_h(t) := F_h(t)\ell_m$ is an operational torque which is generated by the force of the human operator $F_h(t)$. $\tau_m(t)$ and $\theta_m(t)$ are the reaction torque and the rotational angle. Physical parameters of this arm are as follows: $J_h$, the moment of inertia of the rotor of the motor; $J_m$, the moment of inertia of the master arm; and $\mu_m$, the coefficient of friction of the motor shaft. The mathematical model of the rigid arm is calculated as

$$\dot{\theta}_m(t) + \dot{\tau}_m(t) + g_m \gamma_m(t),$$

(1)

where $\gamma_m(t)$ and $g_m$ are the system noise which denotes a white Gaussian noise and the coefficient of the system noise, respectively.

A state space model of Eq. (1) can be written as follows:

$$\dot{x}_m(t) = A_m x_m(t) + B_m u_m(t) + G_m \gamma_m(t),$$

(2)

where $x_m(t) := [ \theta_m(t) \dot{\theta}_m(t) ]^T$ is defined as the state vector and $u_m(t) := [ 0 \tau_m(t) ]^T$ is defined as the control input.

2.2 High-geared Servomotor

The slave arm is driven by a high-geared servomotor in this paper. Thus, the high-geared servomotor should be modeled for introducing in the system. Fig. 3 shows the block diagram of this servomotor. As seen in this figure, this servomotor consists of a high-geared DC motor and a PD feedback controller. $\Theta_{com}(s) := L[\theta_{com}(t)]$ and $\Theta(s) := L[\theta(t)]$ are Laplace transforms of the reference angle and the output angle, respectively. Since the DC motor is controlled by the PD controller, the applied voltage $V(s)$ is represented as:

$$V(s) = K_P (\Theta_{com}(s) - \Theta(s)) + K_D s \{ \Theta_{com}(s) - \Theta(s) \},$$

(3)
Then, by applying the inverse Laplace transform \( \Theta(s) \) and the mathematical model of the DC motor controlled by this torque.

Fig. 4 depicts the parallel-structured single-link flexible slave arm.

![Parallel-Structured Single-Link Flexible Slave Arm](image)

**Fig. 4:** Schematic drawing of the parallel-structured flexible slave arm.

Fig. 5 depicts the parallel-structured single-link flexible arm.

![Parallel-Structured Single-Link Flexible Arm](image)

**Fig. 5:** Schematic drawing of the simplified model of the flexible slave arm.

where \( K_P \) and \( K_D \) are the proportional and derivative gains.

The control torque \( T(t) := T(s)(:= L[\tau(t)]) \) can be calculated by considering the transfer function from \( \Theta_{\text{com}}(s) \) to \( \Theta(s) \) and the mathematical model of the DC motor [13]. Then, by applying the inverse Laplace transform to \( T(s) \), the control torque \( \tau(t) \) is expressed as

\[
\tau(t) = k_f K_P \{ \dot{\Theta}_{\text{com}}(t) - \dot{\Theta}(t) \} + \frac{k_r K_D}{R} \{ \dot{\Theta}_{\text{com}}(t) - \dot{\Theta}(t) \} - \frac{k_c k_r}{R} \dot{\Theta}(t),
\]

where \( k_r \) is the torque constant, \( k_c \) is the back electro motive force constant and \( R \) is the internal resistance of the coil in the DC motor. The flexible slave arm is controlled by this torque.

### 2.3 Nonlinear Flexible Slave Arm

Fig. 4 depicts the parallel-structured single-link flexible arm which is employed as the slave arm in this research. This arm consists of a pair of uniform Euler-Bernoulli beams. A hub unit and a tip-mass are clamped by both ends of each beam. The mathematical model of this arm is very difficult because of highly complex nonlinear differential equations. Thus, for sake of simplicity, the parallel-structured single-link flexible arm is approximated as the single-link flexible arm (shown in Fig. 5) since the displacement of both beams can be regarded as equal due to the construction of this arm [14].

A simplified single-link flexible arm depicted in Fig. 5 consists of an uniform Euler-Bernoulli beam. The unit hub and the tip-mass are clamped by both ends of this arm. \( OXY \) is the inertial Cartesian coordinate system and \( Ox \) is the rotating coordinate system. The length and the rotational angle are \( \ell \) and \( \theta(t) \), respectively. The transverse displacement is \( u(t,x) \).

Physical parameters as follows: \( \rho \) and \( S \) are the uniform mass density and the cross section; \( EI \), the uniform flexural rigidity (where \( E \) is Young’s modulus and \( I \) is the second moment of cross sectional area); \( \mu \) is the coefficient of friction of the motor shaft; \( c_D \) is the coefficient of Kelvin-Voight type damping; \( J_0 \) is the inertia moment of the motor shaft; and \( m \) is the mass of the tip-mass which is regarded as the point mass.

The total kinetic energy \( T(t) \) and the potential energy \( U(t) \) are expressed as

\[
T(t) = T_h(t) + T_b(t) + T_{tm}(t)
\]

\[
U(t) = \int_0^\ell \frac{1}{2} EI \{ u''(t,x) \}^2 \, dx
\]

\[
T_h(t) = \frac{1}{2} J_0 \dot{\theta}^2(t)
\]

\[
T_b(t) = \int_0^\ell \frac{1}{2} \rho S \left\{ \left( x \hat{\theta}(t) + \dot{u}(t,x) \right)^2 + u^2(t,x) \dot{\theta}^2(t) \right\} \, dx
\]

\[
T_{tm}(t) = \frac{1}{2} m \left\{ \left( \ddot{u}(t) + \dot{u}(t) \dot{\theta}(t) \right)^2 + \{ \ddot{u}(t) \dot{\theta}(t) \}^2 \right\},
\]

where \( \ddot{u}(t) := u(t, \ell) \); \( U(t) \) is the bending strain energy; \( T_h(t) \) is the rotational kinetic energy of the hub; and \( T_b(t) \) and \( T_{tm}(t) \) are the translational kinetic energy of the beam and tip-mass.

The virtual work \( \delta W(t) \) is represented as

\[
\delta W(t) = - \frac{\partial F_0(t)}{\partial \theta} \delta \theta - \int_0^\ell \frac{\partial F(t,x)}{\partial u'} \delta u' \, dx + \tau(t) \delta \theta,
\]

where \( F_0(t) \) is the dissipation function of the rotation and \( F(t,x) \) is the dissipation function of the inertial damping. These functions are defined as

\[
F_0(t) = \frac{1}{2} \mu \dot{\theta}^2(t), \quad F(t,x) = \frac{1}{2} c_D I \{ \dot{u''}(t,x) \}^2.
\]

By means of the Hamilton’s principle, the mathematical models of the motor shaft and the beam are given as

\[
J_0 \ddot{\theta}(t) + \mu \dot{\theta}(t) + m \ddot{u}(t) \left\{ 2 \dot{u}(t) \dot{\theta}(t) + \ddot{u}(t) \ddot{\theta}(t) \right\} - c_D I \{ \dot{u''}(t,0) - \dot{u''}(t,\ell) \} - E I \{ u''(t,0) - u''(t,\ell) \} = \tau(t)
\]
\[
+ \int_0^t \rho S \left\{ 2u(t, x) \dot{\bar{u}}(t, x) \dot{\bar{\theta}}(t) + u^2(t, x) \ddot{\bar{\theta}}(t) \right\} dx \\
+ \int_0^t \rho S xu(t, x) \dot{\bar{\theta}}^2(t) dx + m\ell \ddot{\bar{u}}(t) \ddot{\bar{\theta}}(t) \\
= \tau(t) + \int_0^t g_s x \gamma_s(t, x) dx \tag{12}
\]

where \(\gamma_s(t, x)\) and \(g_s\) denote the system noise which is defined as a white Gaussian noise and the coefficient for the system noise, respectively. The boundary and initial conditions are given as

\[
\text{B.C.: } u(t, 0) = u'(t, 0) = u''(t, \ell) = 0 \tag{14} \\
\text{I.C.: } u(0, x) = \ddot{u}(0, x) = 0. \tag{15}
\]

The mathematical model of the flexible arm should be rewritten as the finite-dimensional system to design a state estimator for reducing an effect of a random delay. \(x_s(t)\) indicates a state vector which includes the states of the flexible arm such as \(\ddot{\theta}(t)\), \(\dot{\theta}(t)\), \(u(t, x)\) and \(\ddot{u}(t, x)\). Hence, the state space model of the nonlinear flexible slave arm can be defined as follows:

\[
\dot{x}_s(t) = f_s[x_s(t)] + B_s u_s(t) + G_s \gamma_s(t). \tag{16}
\]

\(f_s[x_s(t)]\) has nonlinear terms because the flexible arm employed in this research is derived as the nonlinear system. To design the extended Kalman filter, the Taylor series expansion around the state estimate is applied to Eq. (16). Due to this procedure, the linearized term with respect to \(f_s[x_s(t)]\) is obtained as follows:

\[
f_s[x_s(t)] = f_s[\hat{x}_s(t)] + \frac{\partial f}{\partial x_s} \bigg|_{x_s = \hat{x}_s} (x_s(t) - \hat{x}_s(t)) \tag{17} \\
= f_s[\hat{x}_s(t)] + F_{x_s}(x_s(t) - \hat{x}_s(t)), \tag{18}
\]

where \(\hat{x}_s\) is the state estimate. \(F_{x_s}\) is defined as \(\partial f/\partial x_s\). Substituting Eq. (18) into Eq. (16), we have

\[
\dot{\hat{x}}_s(t) = f_s[\hat{x}_s(t)] + F_{x_s}(x_s(t) - \hat{x}_s(t)) + B_s u_s(t) + G_s \gamma_s(t) \tag{19} \\
= F_{x_s} x_s(t) + [f_s[\hat{x}_s(t)] - F_{x_s} \hat{x}_s(t)] + B_s u_s(t) + G_s \gamma_s(t) \tag{20} \\
= F_{x_s} x_s(t) + B_s u_s(t) + G_s \gamma_s(t). \tag{21}
\]

where \(B_s u_s(t)\) is redefined as \(f_s[\hat{x}_s(t)] - F_{x_s} \hat{x}_s(t) + B_s u_s(t)\). Therefore, the state space model of the nonlinear flexible slave arm can be defined as the linearized state space model Eq. (21). The extended Kalman filter is designed by using Eq. (21).

3 Modeling of Communication Network Delay

The communication network modeled in this research causes the random delay. Generally, the random delay due to the real communication network has the log normal distribution. However, the random delay is modeled by calculating the sum of an average time delay and a randomness since it is difficultly modeled that the function has the log normal distribution. Hence, the random delay is modeled as \(T + \gamma_o(t)\). \(T\) is the average time delay and \(\gamma_o(t)\) is the randomness. The random delay is defined as

\[
\gamma_o(t) = \begin{cases} 
\gamma(t) & \text{for } \gamma_o(t) > -T \\
0 & \text{otherwise}
\end{cases} \tag{22}
\]

where \(\gamma(t)\) is the white Gaussian noise. Its mean and its covariance are \(\mathcal{E}[\gamma(t)] = 0\) and \(\mathcal{E}[\gamma^2(t)] = R\). Because it is considered that the covariance of \(\gamma(t)\) holds \(R \ll T^2\), \(\gamma_o(t)\) can be regarded as the white Gaussian noise \(\gamma(t)\).

4 Design of Extended Kalman filter

To reduce the effect of the random delay, the extended Kalman filter is designed as the state estimator. The state space model of the master and slave arms are derived in the previous section. In Section 2.3, the linearized state space model of the nonlinear flexible slave arm is derived by means of the Taylor series expansion form. To do this procedure, the extended Kalman filter can be designed as same as the Kalman filter for reducing the effect of the random delay [12].

An ordinary time-invariant linear stochastic system with the random delay is considered to derive the extended Kalman filter. This system is expressed as

\[
dx(t) = Ax(t)dt + Bu(t)dt + Gdw_s(t) \tag{23} \\
dy(t) = Cx(t - (T + \gamma(t)))dt \tag{24}
\]

where \(x(t) \in \mathbb{R}^m\) is the state vector; \(y(t) \in \mathbb{R}^n\), the observation vector; \(u(t) \in \mathbb{R}^1\), a control input; and \(dw_s(t)\), an increment of Wiener process with zero-mean and its covariance \(Q_s := \mathcal{E}[dw_s^2(t)]\). Now, \(dw_s(t) := \gamma_o(t)dt\). \(\gamma_o(t)\) is the system noise and is defined as a white Gaussian noise.

The Taylor series expansion form is applied to the state vector \(x(t - (T + \gamma(t)))\) around \(t_s := t - T\) in the observation system. Substituting Eq. (23) into the resultant function, we have

\[
dy(t) = Cx(t_s)dt - C \{Ax(t_s) + Bu(t_s)\} dw_o(t), \tag{25}
\]

where \(dw_o(t)\) is defined as \(\gamma(t)dt\) and express an increment of Wiener process with zero-mean and its covariance \(R_o := \mathcal{E}[dw_o^2(t)]\). In Eq. (25), the multiplicative noise appears as the product of the state \(x(t_s)\) and the random variable \(\gamma(t)\). Thus, the extended Kalman filter.
should be designed to reduce the multiplicative noise. To do this aim, an innovation process $dv(t)$ is defined. Then, the correlation function of $dv(t)$ is calculated as

$$E\{dv(t)dv^T(t)\} = C[\Pi(t_i)A^T + BQ_uB^T]RC^T,$$

(26)

where $\Pi(t_i)$ is the autocorrelation matrix value of the state and is defined as $E\{x(t_i)x^T(t_i)\}$. $Q_u$ is the autocorrelation value of the input and is defined as $E\{u^2(t_i)\}$. The state estimate $\hat{x}(t_i|t_s)$ can be derived by applying the orthogonal projection [15]. The control input, $u(t_i)$ can not be obtained because this signal is also get through the communication network. Finally, the equations of $x(t_i|t_s)$, $P(t_i|t_s)$ and $\Pi(t_i|t_s)$ are represented as follows:

$$d\hat{x}(t_i|t_s) = A\hat{x}(t_i|t_s)dt + Bu(t - (T + \gamma(t)))dt + P(t_i|t_s)C^T[C[A\Pi(t_i)A^T + BQ_uB^T]RC^T]^{-1} \times \{dy(t) - C\hat{x}(t_i|t_s)dt\}$$

$$\dot{P}(t_i|t_s) = AP(t_i|t_s) + P(t_i|t_s)A^T + GQ_aG^T - P(t_i|t_s)C^T[C[A\Pi(t_i)A^T + BQ_uB^T]RC^T]^{-1} \times CP(t_i|t_s)$$

As seen in these equations, the estimation error covariance $P(t_i|t_s)$ is the Ricatti differential equation and the autocorrelation function of the state $\Pi(t_i)$ is the Lyapunov differential equation.

5 Design of Controllers

The controllers to generate the reaction torque $\tau_m(t)$ and the reference angle $\theta_{com}(t)$ are defined by reference to our previous research [11]. The PD-controller generates the reaction torque $\tau_m(t)$ for the master arm and the PDS-controller generates the reference angle $\theta_{com}(t)$ for the high-gear servomotor. These controllers are defined as

$$\tau_m(t) = K_{Pm}\{\hat{\theta}(t_i|t_s) - \theta_m(t)\} + K_{Dm}\{\hat{\theta}(t_i|t_s) - \bar{\theta}(t)\}$$

$$f(t) = \frac{R}{k_r K_D}\left[K_{Ps}\{\hat{\theta}(t_i|t_s) - \theta(t)\} + K_{Ds}\{\hat{\theta}(t_i|t_s) - \dot{\theta}(t)\} + KS\{c_D I u''(t, 0) - u''(t, \ell)\} + EI\{u''(t, 0) - u''(t, \ell)\}\right] - \frac{k_r K_P}{R}\{\theta_{com}(t) - \theta(t)\} + \frac{(k_m + K_D)k_r}{R}\hat{\theta}(t),$$

(30)

(31)

where $K_{Ps}$ is the proportional gain; $K_{Ds}$, the derivative gain; and $K_S$, the strain gain. $i$ indicates the master arm or the slave arm, i.e. $i = m, s$. Since $f(t)$ is defined as $\dot{\theta}_{com}(t)$, the reference angle for the high-gear servomotor $\theta_{com}(t)$ is obtained by integrating $f(t)$.

6 Numerical Simulation

By using numerical simulation, the performance of the proposed bilateral control system is demonstrated. The Matlab and the Simulink are used to achieve the numerical simulation.

6.1 Setup

It is assumed that the flexible slave arm is made of the phosphor bronze. Its length is $\ell = 0.3[m]$, thickness is $1.0 \times 10^{-3}[m]$ and width is $4.0 \times 10^{-2}[m]$. The physical parameters of the rigid master arm, the flexible slave arms and the high-gear servomotor are listed in Tables 1 to 3.

The initial conditions of the proposed system are set as $\theta_m(0) = 0[rad]$, $\theta_m(0) = 0[rad/s]$, $\theta(0) = 0[rad]$, $\dot{\theta}(0) = 0[rad/s]$, $u(0, x) = 0[m]$ and $u(0, x) = 0[m/s]$. Moreover, the average time delay $T$ is set as 0.25.[s]

6.2 Simulation Results

The results of the numerical simulation is shown in Figs. 6 and 7. In Fig. 6, the solid line is the angle of the slave arm $\theta(t - (T + \gamma(t)))$, the solid red line is the estimated angle of the slave arm $\hat{\theta}(t_i|t_s)$. The random delay for the numerical simulation is depicted in Fig. 6(b). As seen in these figure, it can be considered that the proposed EKF can estimate the state value of the slave arm.

Table 1: Physical parameters of the master arm.

| Symbol | Value |
|--------|-------|
| $J_h$  | 0.70  [kg·m²] |
| $\mu_m$ | $3.03 \times 10^{-2}$ [kg·m²·s] |
| $m_m$  | $29.05 \times 10^{-3}$ [kg] |
| $I_m$  | 0.30  [m] |
| $J_m$  | $6.54 \times 10^{-4}$ [kg·m²] |

Table 2: Physical parameters of the slave arm.

| Symbol | Value |
|--------|-------|
| $J_0$  | 0.70  [kg·m²] |
| $\mu$  | $3.03 \times 10^{-2}$ [kg·m²·s] |
| $\ell$  | 0.30  [m] |
| $\rho$ | $8.8 \times 10^{3}$ [kg/m³] |
| $S$   | $4.0 \times 10^{-3}$ [m²] |
| $E$   | $1.1 \times 10^{11}$ [Pa] |
| $I$   | $8.33 \times 10^{-13}$ [m⁴] |
| $c_D$ | $1.93 \times 10^{9}$ [N·s/m²] |
| $m$   | 0.245 [kg] |
Table 3: Physical parameters of the high-geared servomotor.

| Symbol | Value       |
|--------|-------------|
| $K_p$  | 32 [V/rad]  |
| $K_d$  | 32 [V/(rad/s)] |
| $k_e$  | 2.6 [V/(rad/s)] |
| $k_τ$  | 2.6 [N/A]    |
| $R$    | 1.73 [Ω]     |

In Fig. 7, the solid line is the angle of the master arm $θ_m(t)$, the dashed lines are the estimated angle of the master arm $θ_m(t_s|t_s)$ and the slave arm $θ(t)$. The tip’s displacement of the flexible slave arm $u(t, x)$ is depicted in Fig. 7(b). The torques $τ_m(t)$ and $τ(t)$ are depicted in Fig. 7(c). In this figure, the solid line is the reaction torque for the master arm $τ_m(t)$ and the dashed line is the control torque for the slave arm $τ(t)$.

As seen in this simulation results, the estimated angle of the rigid master arm $θ_m(t_s|t_s)$ is estimated well and the angle of the flexible slave arm $θ(t)$ traces the angle of the rigid master arm well. Thus, the proposed extended Kalman filter estimates the state of the rigid master arm well. The tip’s displacement $u(t, x)$ vibrates during the numerical simulation. Because its vibration does not diverge, it can be considered that the PDS-controller is well-designed. The reaction torque for the rigid master arm $τ_m(t)$ is generated by differences of the angle and the angular velocity between the master arm and the slave arm. This torque acts on the human operator. Since the reaction torque vibrate a little, the human operator will receive an uncomfortable feeling.

7 Conclusions

The bilateral control system of the nonlinear flexible master-slave arms with the random delay was investigated. The mathematical models of the rigid master and nonlinear flexible slave arms were modeled by using the Hamilton’s principle and the high-geared servomotor employed to drive the slave arm was modeled. The random delay was defined as a sum of the knowing average time delay and the white Gaussian noise. The state space models of the master and slave arms were derived to design the extended Kalman filter. Since the slave arm was the nonlinear system, the Taylor series expansion form was applied to this system for deriving the linearized state space model. Moreover, to treat the random delay explicitly, the Taylor series expansion form was applied to the observation system including the random delay. By using the orthogonal projection, the extended Kalman filter was derived to reduce the effect of the random delay. This proposed filter had the estimate state system, the Ricatti equation for the estimation error covariance and the Lyapunov differential equation for the autocorrelation of the states. The effect of the random component of the delay is appeared by using the Taylor series expansion form. It is assumed
that the behavior of the proposed system become instability when the effect of the random component is large. However, it is expected that the proposed Kalman filter can reduce the effect of the random component of the delay. The reaction torque for the master arm and the control input for the slave arm were generated by the PD- and PDS-controllers. The performance of the proposed system was demonstrated by using the numerical simulation. As seen in the simulation results, the proposed extended Kalman filter reduced the effect of the random delay well. Furthermore, because the angle of the flexible slave arm traced the estimated angle of the rigid master arm well, the PD- and PDS-controllers were well-designed to generate torques.

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