PDS Based Bilateral Control System for Nonlinear Flexible Master-Slave Arms with Random Delay Considering Contact with Obstacle*

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A bilateral control system connected by a communication network is investigated in this research. A rigid arm is employed as a master arm. A flexible arm is employed as a slave arm and is modeled by a nonlinear system. Moreover, the slave arm collides with an obstacle during its motion. The communication network causes a random delay. Hence, signals become noisy due to this delay. An extended Kalman filter is designed to reduce the effect of the random delay. Numerical simulations are demonstrated to confirm the performance of the proposed system.

1. Introduction

Population slowly decrease in recent years and robots gain increasing attention as labor power. On the other hand, IoT (Internet of Things) technology is widely utilized for human life. This technology is more introduced to connect anything and everything. If robots are used in general environments such as houses, offices and so on, there are naturally connected with network. Hence, teleoperation technologies are very important and this technologies should be realized without special equipments. In this research, a bilateral control system is investigated as one of teleoperation technologies. The proposed system consists of a rigid master arm and a flexible slave arm. Both arms are connected a communication network which is considered an ordinary network such as local area networks (LAN), wide area networks (WAN), and wireless LANs. Since the network causes a random delay, signals become noisy due to this delay.

A lot of researchers have discussed arms, teleoperation technologies and networked systems. Matsuno et al. introduced a proportional derivative and strain (PDS) controller for a flexible beam and Hoshino et al. constructed a bilateral system for a flexible master-slave manipulator [1,2]. Namerikawa studied a control strategy for bilateral systems with time-varying delay [3]. These researches does not consider random delay. Liu et al. discussed a model predictive control for networked system [4]. Guo et al. proved the exponential stability of a discrete-time system with random delay and Schenato proposed an optimal estimator with random delay [5,6]. The random delay in these studies was not modeled by a stochastic model.

A networked bilateral control system was investigated in our previous research. Fig. 1 shows our networked bilateral control system which consists of master and slave arms and a network. The network was modeled by a time-varying delay or a random delay. The time-varying delay was represented as a time-variant system and the random delay was represented by the sum of the average delay and the white Gaussian noise. Since the network causes a random delay, signals become noisy due to this delay.

When the slave arm collided with an obstacle during its motion, it was confirmed that the slave arm could trace the master arm and did not vibration [9]. However, nonlinear terms were ignored because the flexible slave arm was modeled as the linearized system in [9].

In this research, a bilateral control system of nonlinear flexible master-slave arms with random delay affected by a contact force is investigated. This system consists of a rigid master arm and a flexible slave arm. Hamilton’s principle is used to derive mathematical models. The flexible arm is modeled as a nonlinear system and its model includes a contact force.
A sum of an average delay and a Gaussian noise is employed as the model of the random delay. An extended Kalman filter is designed as a state estimator because the flexible arm is the nonlinear system. The PD-controller is designed to generate the reaction torque for the master arm and the PDS-controller is also designed to calculate the reference angle for the slave arm. Numerical simulations are demonstrated to confirm the performance of the proposed system.

2. Mathematical Models

In this research, the bilateral control system consists of rigid and flexible arms. The flexible arm is employed as a nonlinear system and is driven by a high-geared servomotor. Mathematical models of both arms and the servomotor are derived in this section.

2.1 Rigid Master Arm

Fig. 2 shows the rigid arm which consists of an uniform rigid rod and a hub. As seen in this figure, \( O_mX_mY_m \) is the inertial Cartesian coordinate system. \( \ell_m \) and \( m_m \) are the length and mass. Because this arm is operated by a human operator, the operating torque \( \tau_h(t) \) is generated by the operating force \( F_h(t) \) which is added at the end of this arm. Thus, \( \tau_h(t) \) is calculated by \( F_h(t) \ell_m \). \( \theta_m(t) \) is the rotational angle. \( \tau_m(t) \) is the reaction torque which is generated by a DC motor. \( J_h \) and \( J_m \) are the moments of inertia of the motor’s rotor and the master arm, respectively; and \( \mu_m \) is the coefficient of friction of the motor shaft. Therefore, the mathematical model of the rigid arm is expressed as

\[
\left( J_h + J_m + \frac{1}{4} m_m \ell_m^2 \right) \ddot{\theta}_m(t) + \mu_m \dot{\theta}_m(t) = \tau_h(t) + \tau_m(t) + g_m \gamma_m(t),
\]

where \( \gamma_m(t) \) is the system noise which is defined as a Gaussian noise process. \( g_m \) is the coefficient of the system noise.

2.2 High-geared Servomotor

A high-geared servomotor consists of a high-geared DC motor and a PD-controller and drives a flexible arm. The block diagram of this servomotor is shown in Fig. 3. As seen in this figure, \( \Theta_{com}(s) := L[\theta_{com}(t)] \) is a reference angle and \( \Theta(s) := L[\theta(t)] \) is an output angle where \( L\{\cdot\} \) represents the Laplace transform.

The control torque \( \tau(t) \) is added to the flexible arm. This torque represented as follow is calculated by considering the mathematical model of the DC motor and applying the inverse Laplace transform [10].
Fig. 4 Schematic drawing of the parallel-structured flexible slave arm

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

\[\tau(t) = \frac{k_r K_P}{R} \left\{ \dot{\theta}_{com}(t) - \theta(t) \right\} + \frac{k_r K_D}{R} \left\{ \ddot{\theta}_{com}(t) - \dot{\theta}(t) \right\} - \frac{k_r K_P}{R} \ddot{\theta}(t), \]

where \(K_P\) is the proportional gain; \(K_D\) is the derivative gain; \(k_r\) is the back electromotive force constant; \(k_r\) is the torque constant; and \(R\) is the internal resistance of the coil in the DC motor.

### 2.3 Flexible Slave Arm

The parallel-structured single-link flexible arm is employed as the slave arm in this research (shown in Fig. 4). As seen in this figure, a pair of uniform Euler-Bernoulli beams construct the flexible arm. A hub unit and a tip-mass are clamped by an end of each beams. Since the centrifugal force is assumed to be sufficiently small and the displacement of both beams can be considered equal, the parallel-structured single-link flexible arm can be simplified as the single-link flexible arm (shown in Fig. 5) \[11\]. As seen in this figure, the simplified flexible arm consists of an uniform Euler-Bernoulli beam and one of the end is fixed on the unit hub and the other end is also fixed on the tip-mass. To derive the mathematical model of this flexible arm, the boundary conditions are the same as the original arm.

\(OXY\) and \(Oxy\) are the inertial Cartesian and the rotating coordinate systems, respectively. \(\ell\) and \(\theta(t)\) are the length and the rotational angle. \(u(t, x)\) is the transverse displacement of the beam from the \(x\)-axis. The physical parameters are defined as follows: \(S\) and \(\rho\) are the cross sectional and the uniform mass density, respectively; \(EI\) is the uniform flexible rigidity \((E\) is Young’s modulus and \(I\) is the second moment of the cross-sectional area); \(J_0\) is the inertial moment of the motor shaft; \(c_D\) is the coefficient of Kelvin-Voigt-type damping; \(\mu\) is the coefficient of friction of the motor shaft; and \(m\) is the mass of the tip-mass which is assumed as a point mass.

A rigid obstacle is fixed at \(x_c\) and the flexible arm contact with this obstacle at \(x = x_c\) \((0 < x_c < \ell)\). The energy of the flexible arm does not dissipate due to the collision since this obstacle is fixed and the rigid. Hence, the interaction between the flexible arm and the obstacle does not considered in this research. As seen in Fig. 5, \(\phi_0\) is the rotational angle between the \(OX\)-axis and the line from \(O\) to the collision point. The geometric constraint between the flexible arm and the obstacle expressed as

\[\psi(t) = u(t, x_c) - x_c \tan(\phi_0 - \theta(t)) = 0.\]  (3)

For deriving the mathematical model of the flexible arm, the total kinetic energy \(T(t)\) and the potential energy \(U(t)\) are calculated as follows.

\[T(t) = T_h(t) + T_b(t) + T_{tm}(t)\]  (4)
\[U(t) = \int_0^\ell \frac{1}{2} EI \left\{ u''(t, x) \right\}^2 dx, T_h(t) = \frac{1}{2} J_0 \dot{\theta}^2(t)\]  (5)
\[T_b(t) = \int_0^\ell \frac{1}{2} S \left\{ \dot{x} \dot{\theta}(t) + u(t, x) \right\}^2 + u^2(t, x) \dot{\theta}^2(t) \right] dx\]  (6)
\[T_{tm}(t) = \frac{1}{2} m \left\{ \dot{\theta}(t) + \dot{u}(t) \right\}^2 + \right\{ \ddot{u}(t) \dot{\theta}(t) \}^2 \right\},\]  (7)

where \(\dot{u}(t) := u(t, \ell)\). \(T_h(t)\) and \(T_b(t)\) are the energies of the rotation of the unit-hub and the translation of the flexible beam, respectively; \(T_{tm}(t)\) is the energy of the translation of the tip-mass; and \(U(t)\) is the bending strain energy of the flexible beam. The prime represented the derivative with respect to \(x\), i.e., \(\{ \cdot \}' = \partial / \partial x\).

The following equation is obtained by using Hamilton’s principle.

\[\int_{t_1}^{t_2} \left\{ \delta T(t) - \delta U(t) + \delta W(t) + s \delta \psi(t) \right\} dt = 0,\]  (8)

where \(\delta W(t)\) is the virtual work \(8\). \(s\) is the Lagrange multiplier. This multiplier can be considered as a contact force \(s(t)\). Therefore, the mathematical model of the flexible arm including the contact force is represented as

\[J_0 \ddot{\theta}(t) + \mu \dot{\theta}(t) + m \ddot{u}(t) \left\{ 2 \dot{u}(t) \dot{\theta}(t) + \ddot{u}(t) \ddot{\theta}(t) \right\} + c_D I \left\{ \dddot{u}(t, 0) - \dddot{u}(t, \ell) \right\} - EI \left\{ u''(t, 0) - u''(t, \ell) \right\}\]
\[ + \int_0^\ell \rho S \left\{ 2u(t,x)\dot{u}(t,x)\dot{t}(t) + u^2(t,x)\ddot{t}(t) \right\} dx \\
+ \int_0^\ell \rho S u(t,x)\ddot{t}(t) dx + m\ddot{u}(t)\ddot{t}(t) \\
= \tau(t) + s(t)x + \int_0^\ell g_s\gamma_s(t,x) dx \tag{9} \]

\[ \rho S\ddot{u}(t,x) + c_p I\ddot{u}^m(t,x) + EI\ddot{u}^m(t,x) + \rho S\ddot{t}(t) \]
\[ + m(\ddot{t}(t) + \ddot{t}(t)) - \rho S u(t,x)\ddot{t}(t) \]
\[ - m\ddot{u}(t)\ddot{t}(t)(x - t) = s(t)\dot{x}(x - x_0) + g_s\gamma_s(t,x) \tag{10} \]

where \( \gamma_s(t,x) \) is the system noise and \( g_s \) denotes the coefficient of \( \gamma_s(t,x) \). This system noise is defined as a white Gaussian noise process. The third term and the sixth to eighth terms in L.H.S of eq. (9) and the sixth and seventh terms in L.H.S of eq. (10) are nonlinear terms which indicate Coriolis force and so on.

3. Synthesis of Novel Kalman Filter

Since the communication network causes the random delay, signals become noisy due to this delay. An extended Kalman filter is employed as a state estimator for reducing the effect of the random delay. The linearized state space model of the flexible arm is derived and the Taylor series expansion form is applied [13].

The considered stochastic system is expressed as
\[
dx(t) = Ax(t)dt + Bu(t)dt + Gdw_s(t) \tag{11} \\
dy(t) = Cx(t - (T + \gamma(t)))dt, \tag{12} \]
where \( x(t) \in \mathbb{R}^m \) is the state vector and \( y(t) \in \mathbb{R}^o \) is the observation vector, respectively. \( u(t) \in \mathbb{R}^1 \) is a control input. \( dw_s(t) \) is an increment of Wiener process with zero-mean and its covariance \( Q_s := \mathcal{E}(dw_s^2(t)) \). Now, \( dw_s(t) \) is defined as \( \gamma_s(t) dt \). In eqs. (11) and (12), the matrices \( A, B \) and \( G \) for the rigid master arm and the flexible slave arm are derived by these mathematical model. These matrices are written into detail in [8].

Now, the contact force \( s(t) \) is added to the control input for the slave arm. The matrix \( C \) is the same for the master arm and the slave arm because the angle and the angular velocity are estimated by the estimator. Thus, \( C \) is expressed as \( I \in \mathbb{R}^2 \).

The Taylor series expansion form is applied to the state vector \( x(t - (T + \gamma(t))) \) around \( t_s := t - T \) in eq. (12). The observation system is rewritten as follows by substituting the resultant function.
\[
dy(t) = Cx(t_s)dt - C\{ Ax(t_s) + Bu(t_s) \} dw_s(t), \tag{13} \]
where \( dw_s(t) := \gamma(t) dt \) is an increment of Wiener process with zero-mean and its covariance \( R_s := \mathcal{E}(dw_s^2(t)) \). As seen in this function, the multiplicative noise defined as the product of the state \( x(t_s) \) and the random variable \( \gamma(t) \) appears.

The state estimate \( \hat{x}(t_s|t_s) \) can be obtained [12]. In this research, the control input \( u(t_s) \) cannot be obtained. Therefore, the state estimate are finally represented as
\[
d\hat{x}(t_s|t_s) = A\hat{x}(t_s|t_s)dt + Bu(t - (T + \gamma(t)))dt \\
+ P(t_s|t_s)C^T \left[ C\{ AI(t_s)A^T + BQ_uB^T \} RCT \right]^{-1} \\
\times \{ dy(t) - C\hat{x}(t_s|t_s)dt \} \tag{14} \\
\hat{P}(t_s|t_s) = AP(t_s|t_s) + P(t_s|t_s)A^T + GQ_sG^T \\
\times \{ P(t_s|t_s)C^T \left[ C\{ AI(t_s)A^T + BQ_uB^T \} RCT \right]^{-1} \\
\times CP(t_s|t_s) \}
\hat{H}(t_s) = AI(t_s) + P(t_s)A^T + GQ_sG^T. \tag{15} \]

4. Synthesis of Controllers

The PD-controller is employed to generate the reaction torque for the master arm and the PDS-controller is employed to calculate the reference angle for the slave arm [8]. These controllers are expressed as follows:
\[
\tau_m(t) = K_{pm} \left\{ \dot{\theta}(t_s|t_s) - \theta_m(t) \right\} \\
+ K_{dm} \left\{ \dot{\theta}(t_s|t_s) - \dot{\theta}_m(t) \right\} \tag{17} \\
f(t) = \frac{R}{k_r K_{Ds}} \left\{ K_{Ps} \{ \dot{\theta}_m(t_s|t_s) - \theta(t) \} \\
+ K_{Ds} \{ \dot{\theta}_m(t_s|t_s) - \dot{\theta}(t) \} \\
+ K_S \{ \nabla t \{ \theta_m(t_s|t_s) - \dot{\theta}(t) \} \} \\
+ E \{ \ddot{u}(t) - \ddot{u}(t, t, t) \} \right\} - \frac{k_r K_{Ps}}{R} \left\{ \theta_{com}(t) - \theta(t) \right\} \tag{18} \\
+ \frac{k_r K_{Ds}}{R} \left\{ \nabla t \{ \theta_{com}(t) - \dot{\theta}(t) \} \right\}, \]

where \( K_{pm} \) and \( K_{Ps} \) are the proportional gains; \( K_{dm} \) and \( K_{Ds} \) are the derivative gains; and \( K_S \) is the strain gain. The control input for the slave arm \( f(t) \) is defined as \( \theta_{com}(t) \), e.g. \( f(t) := \theta_{com}(t) \). Then the reference angle \( \theta_{com}(t) \) is calculated by integrating \( f(t) \) to give the high-geared servomotor.

5. Numerical Simulations

The numerical simulations are accomplished to confirm the performance of the proposed bilateral control system. Matlab and Simulink are used for these simulations. Undermentioned things are confirmed by demonstrating the simulations.

(1) The flexible slave arm tracks the rigid master arm.

(2) The designed extended Kalman filter can reduce the effect of the random delay.

(3) The nonlinear flexible slave arm does not become instability due to the collision.

5.1 Setup

The flexible arm employed in this research is made from phosphor bronze. The thickness and width are \( 1.0 \times 10^{-3}[\text{m}] \) and \( 4.0 \times 10^{-2}[\text{m}] \), respectively. The physical parameters of the proposed system are listed in Table 1 to Table 3.

The initial values are set as \( \theta_m(0) = 0[\text{rad}], \dot{\theta}_m(0) = 0[\text{rad/s}], \theta(0) = 0[\text{rad}], \dot{\theta}(0) = 0[\text{rad/s}], u(0, x) = 0[\text{m}], \) and \( \dot{u}(0, x) = 0[\text{m/s}] \). The average time delay \( T \) is set
The variance of $\gamma_m(t)$ and $\gamma_s(t)$ are set as 1.0 and the variance of $\gamma(t)$ is set as $10^{-3}$. Furthermore, the collision position $x_c$ and angle $\phi_0$ are written in a caption of each simulation results.

5.2 Sample Process

Numerical simulation results of the sample process of the proposed bilateral control system are shown in Fig. 6. In this case, the flexible slave arm does not collide with the obstacle and the extended Kalman filter designed in this paper does not use. As seen in this figure, the top figure is the rotational angle; the middle figure is the total energy; and the lower middle figure are the angle of the master arm $\theta$ and the estimated angle $\hat{\theta}$ well. It is understood that the motion of the slave arm well due to the designed controller. However, the rotational angle through the network becomes noisy as 0.25[s]. The variance of $\gamma_m(t)$ and $\gamma_s(t)$ are set as 1.0 and the variance of $\gamma(t)$ is set as $10^{-3}$. Furthermore, the collision position $x_c$ and angle $\phi_0$ are written in a caption of each simulation results.

5.3 Results

Figs. 7-10 depict the results of the numerical simulations. Top figures are the rotational angle. Middle figures are the tip’s displacement. Bottom figures are the torques. As seen in (a) of each figures, the solid lines are the angle of the master arm $\theta_m(t)$ and the dashed lines are the estimated angle of the flexible arm $\hat{\theta_s}(t)$. As seen in (c) of each figures, the solid lines are the reaction torque $\tau_m(t)$ and the dashed lines are the contact force $x_c, s(t)$. Since the estimated angle $\hat{\theta}(t|s)$ tracks the angle $\theta_m(t)$ well, the flexible slave arm tracks the rigid master arm well. It is understood that the motion of the slave arm is constrains by the collision because the estimated angle does not reach the desired angle of the master arm. The tip’s displacement quickly converges to zero due to the designed PDS-controller when the slave arm does not collide. However, when the slave arm collides with the obstacle, the tip’s displacement and the contact torque $x_c, s(t)$ have the large values.

![Fig. 6 Numerical simulation results of sample process](image-url)

due to the random delay.

Table 1 Physical parameters of the rigid master arm

| Symbol | Value       |
|--------|-------------|
| $J_0$  | 0.70 [kg\cdot m^2] |
| $\mu_m$ | $3.03 \times 10^{-2}$ [kg\cdot m^2\cdot s] |
| $m_m$  | $29.05 \times 10^{-3}$ [kg] |
| $l_m$  | 0.30 [m] |
| $J_m$  | $6.54 \times 10^{-4}$ [kg\cdot m^2] |

Table 2 Physical parameters of the flexible slave arm

| Symbol | Value       |
|--------|-------------|
| $J_0$  | 0.70 [kg\cdot m^2] |
| $\mu$  | $3.03 \times 10^{-2}$ [kg\cdot m^2\cdot s] |
| $\ell$ | 0.30 [m] |
| $\rho$ | $8.8 \times 10^3$ [kg/m^3] |
| $S$    | $4.0 \times 10^5$ [m^2] |
| $E$    | $1.1 \times 10^{11}$ [Pa] |
| $I$    | $8.33 \times 10^{-13}$ [m^4] |
| $c_D$  | $1.93 \times 10^9$ [N\cdot s/m^2] |
| $m$    | 0.245 [kg] |

Table 3 Physical parameters of the high-geared servomotor

| Symbol | Value       |
|--------|-------------|
| $K_P$  | 32 [V/\text{rad}] |
| $K_D$  | 32 [V/\text{rad}/s] |
| $k_e$  | 2.6 [V/\text{rad}/s] |
| $k_r$  | 2.6 [N/A] |
| $R$    | 1.73 [Ω] |

Fig. 6 Numerical simulation results of sample process
Furthermore, the reaction torque $\tau_m(t)$ also becomes the large value.

Through these numerical simulation results, the proposed system does not become instable. The designed extended Kalman filter can reduce the effect of the random delay. Furthermore, the PD and PDS controllers for generating the reaction torque and the reference angle are well-designed. However, the operator may feel uncomfortable because the reaction torque becomes noisy due to the system noise.

6. Conclusions

In this research, a bilateral control system for nonlinear flexible master-slave arms with random delay was investigated. The flexible slave arm was modeled as the nonlinear system and collided with an obstacle during its motion. Hamilton’s principle was used to derive mathematical models of both arms. The mathematical model of the flexible arm included the collision force and the control torque of this arm was generated by a high-gearered servomotor. The random delay of the network was calculated as the sum of the average delay and the white Gaussian noise. Because the flexible arm was the nonlinear system, the extended Kalman filter was employed as the state estimator. The Taylor series expansion form was applied to the observation system which included the random delay for designing this filter. The reaction torque for the rigid master arm and the reference angle for the flexible slave arm were generated by the PD-controller and the PDS-controller, respectively.

The performance of the proposed bilateral control system was confirmed by numerical simulations. The contact force from the obstacle was generated using the Hertz contact model. Through the simulation results, the designed extended Kalman filter could reduce the effect of the random delay and the reaction torque and the reference angle were generated well by the PD and PDS controllers. Eventually, the flexible slave arm tracked the rigid master arm well and the proposed bilateral control system was stable in spite of the contact force. The simulation results using the nonlinear flexible arm were almost the same as the results using the linearized flexible arm. Therefore, it was found that the nonlinear terms had little effect on the stability of the performance in case of velocity for this research.

The proposed method in this paper can be used some works which are given a desired position, used a flexible thing and connected network. Moreover, since the machine is made of flexible material, it is possible that human and machines work in same place.
Fig. 9 Numerical simulation results ($x_c = 0.25[m]$, $\phi_0 = 0.30[rad]$)

Fig. 10 Numerical simulation results ($x_c = 0.25[m]$, $\phi_0 = 0.60[rad]$)

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