Performance Analysis of a Three-Channel Control Architecture for Bilateral Teleoperation with Time Delay

Ryogo Kubo Member (Keio University, kubo@sum.sd.keio.ac.jp)
Noriko Iiyama Student Member (Keio University, noriko@sum.sd.keio.ac.jp)
Kenji Natori Student Member (Keio University, natori@sum.sd.keio.ac.jp)
Kouhei Ohnishi Senior Member (Keio University, ohnishi@sd.keio.ac.jp)
Hirotaka Furukawa Non-member (NTT DoCoMo, Inc., furukawahiro@nttdocomo.co.jp)

Keywords: bilateral control, acceleration control, time delay, transparency, three-channel architecture, haptics

This paper presents a novel three-channel control architecture for bilateral teleoperation with/without time delay. In concrete terms, this system has two transmission channels of position and force information from the master side to the slave side and one transmission channel of force information from the slave side to the master side. The master controller of the proposed three-channel teleoperation system does not include a position controller, i.e., only force control is implemented in the master side, in order to improve operability in the master side.

Fig. 1 shows a general four-channel architecture for bilateral teleoperation. In Fig. 1, \( \theta_m, \theta_m^s, \theta_m^e, \) and \( \tau_m^e \) are the position of the master robot, the position of the slave robot, the estimated external torque exerted on the master robot and the estimated external torque exerted on the slave robot, respectively. The external torque exerted on the robot \( \tau_m^e \) and \( \tau_m^e \) is estimated by using not a force sensor but the reaction torque observer (RTOB). \( T_1 \) denotes delay time from the master side to the slave side and \( T_2 \) denotes delay time from the slave side to the master side. \( C_1, C_4, C_m \) and \( C_b \) are position control parameters, and \( C_2, C_3, C_5 \) and \( C_6 \) are force control parameters.

In the proposed three-channel control architecture, control parameters are set as (1)–(3).

\[
\begin{align*}
C_1 &= C_2 = C_p(s) \quad \text{.................................. (1)} \\
C_4 &= C_m = 0 \quad \text{.................................. (2)} \\
C_2 &= C_3 = C_5 = C_6 = C_f \quad \text{.................................. (3)}
\end{align*}
\]

Therefore, master and slave acceleration reference values are calculated as (4) and (5)

\[
\begin{align*}
\theta_m^{ref} &= C_f (\theta_m^e + \theta_m^s e^{-T_1}) \quad \text{.................................. (4)} \\
\theta_m^{ref} &= C_f (\theta_m^e - T_1 \theta_m^{ref} - \theta_m^s) - C_f (\theta_m^e e^{-T_1} + \theta_m^{ref}) \quad \text{.................................. (5)}
\end{align*}
\]

where \( C_p(s) = K_p + K_s \) and \( C_f = K_f \) are a position controller and a force controller, respectively. \( K_p, K_s \) and \( K_f \) denote position feedback gain, velocity feedback gain and force feedback gain, respectively.

Fig. 2 shows experimental results with time delay in the case using the proposed three-channel architecture. Virtual and randomly-fluctuating communication time delay (50 [ms] \( < T_1 \), \( T_2 \leq 150 \) [ms]) is inserted into communication channels. In Fig. 2(a), it is shown that the position responses of the master and slave robots almost perfectly tracked each other. In addition, as shown in Fig. 2(b), the operator felt little manipulating force in free motion. The validity of the proposed method was confirmed by experimental results.

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For Bilateral Teleoperation with Time Delay

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Ryogo Kubo∗ Member
Noriko Iiyama∗ Student Member
Kenji Natori∗ Student Member
Kouhei Ohnishi∗ Senior Member
Hirotaka Furukawa∗∗ Non-member

Bilateral control is one of the control methods of teleoperation systems. Human operators can feel reaction force from remote environment by means of this control scheme. This paper presents a novel control architecture for bilateral teleoperation with/without time delay. The proposed bilateral control system has three communication channels between master and slave robots. In concrete terms, this system has two transmission channels of position and force information from the master side to the slave side and one transmission channel of force information from the slave side to the master side. The master controller of the proposed three-channel teleoperation system does not include a position controller, i.e. only force control is implemented in the master side, in order to improve operationality in the master side. The three-channel controller with time delay as well as without time delay gives better performance (higher transparency) than other conventional controllers such as four-channel controllers and so on. In the proposed controller, models of a slave robot and communication time delay are not required differently from conventional methods, and robust acceleration control is achieved by using the disturbance observer (DOB). Hybrid matrices are utilized to analyze four-channel and three-channel control systems. Transmission characteristics of force and position information between master and slave robots are clarified in the analysis. The validity of the proposed method is confirmed by experimental results.

Keywords: bilateral control, acceleration control, time delay, transparency, three-channel architecture, haptics

1. Introduction

Bilateral teleoperation robots have been utilized in space, water, nuclear power plants and so on. In this system, the human operator manipulates the master robot, and then the slave robot tracks the master robot. If the slave robot has contact with the environment, the reaction force from the environment is transmitted to the master side. Therefore, the human operator can feel reaction force from the remote environment as if she/he touches the environment directly(1) (2). By using this scheme, she/he can work safely and effectively.

Transparency is one of the evaluation indices of bilateral teleoperation systems(3). High transparency means that the force control and the position control are achieved perfectly both in the master side and in the slave side. In fact, the force control has to be achieved with accuracy to match master and slave force responses, and the position control has to be also achieved with accuracy to match master and slave position responses. In bilateral control systems, however, decomposition of a bilateral control system into two components, i.e. a force control system and a position control system, is a main problem. These two controllers should be designed independently for ideal bilateral control. For above purpose, some researchers have utilized the disturbance observer (DOB)(4) and mode decomposition(5). In addition, transmission characteristics of force and position information between master and slave robots are clarified by using hybrid matrices in the case without time delay(6).

In teleoperation systems, communication time delay between master and slave robots is also a serious problem. Particularly, the use of passivity-based formalism is very common to design bilateral controllers for teleoperation systems with time delay. Niemeyer et al.(7) defined wave variables based on scattering theory(8), and designed a passivity-based bilateral controller. The Smith predictor is often utilized to compensate time delay effect in bilateral teleoperation(9). However, this method requires a precise slave model and a time delay model. Munir et al.(10) proposed a wave-based controller with the Smith predictor. In this method, the Kalman filter and an energy regulator were utilized to cope with uncertainties of the slave model and unpredictable and varying communication time delay. The communication disturbance observer (CDOB) was proposed to estimate unpredictable and varying communication time delay as network disturbance (ND) and to compensate time delay effect(11)(12). However, the performance is greatly affected by order rearrangement of transmitted data due to network conditions,
since CDOB requires slave models including integral elements.

Meanwhile, there are a lot of bilateral control architectures with/without time delay\(^{(13)}\). The most general architecture is the four-channel architecture which has four communication channels\(^{(15)}\). The controllers utilize the information of the master/slave position and force. In addition, some researchers have been proposed three-channel architectures\(^{(14)}\). For example, Hashtrudi-Zaad et al.\(^{(15)}\) proposed two classes of architectures, the operator-force-compensated (OFC) architecture, which does not have a transmission channel of force information from the slave side to the master side, and the environment-force-compensated (EFC) three-channel control architecture, which does not have a transmission channel of force information from the master side to the slave side. The three-channel architecture proposed by Flemmer et al.\(^{(12)}\) does not have a transmission channel of position information from the slave side to the master side, and it has local position feedback\(^{(16)}\). However, ideal performance (high transparency) cannot be achieved, since these control schemes are not based on robust acceleration control\(^{(10)}\).

In this paper, a novel three-channel architecture for bilateral teleoperation is designed based on acceleration control. The proposed system has three communication channels between master and slave robots. In concrete terms, this system has two transmission channels of position and force information from the master side to the slave side and one transmission channel of force information from the slave side to the master side. The master controller of the proposed system does not include a position controller, i.e. only force control is implemented in the master side, in order to improve operationality in the master side. The three-channel controller with time delay as well as without time delay gives better performance (higher transparency) than other conventional controllers such as two-channel and four-channel controllers. In the proposed controller, models of a slave robot and communication time delay are not required differently from conventional methods, and robust acceleration control is achieved by using DOB. Hybrid matrices are utilized to analyze four-channel and three-channel control systems. Transmission characteristics of force and position information between master and slave robots are clarified in the analysis. The validity of the proposed method is confirmed by experimental results.

The composition of this paper is described as follows. Section 2 presents a general four-channel bilateral controller based on acceleration control. The proposed three-channel architecture and the conventional four-channel architectures are described and analyzed by using hybrid matrices in Section 3. In Section 4, experimental results are shown. Finally, conclusions are described in Section 5.

2. General Bilateral Control based on Acceleration Control

In this section, the disturbance observer (DOB) and the reaction torque observer (RTOB) implemented for robust acceleration control are presented. In addition, a general four-channel architecture for bilateral teleoperation based on acceleration control is described.

2.1 Disturbance Observer (DOB) In actual robot control, disturbance torque \(\tau_{\text{dis}}\) as well as generated torque is exerted on a robot. The disturbance observer (DOB) estimates disturbance torque \(\tau_{\text{dis}}\) including external torque \(\tau_{\text{ext}}\) and computes compensation current \(I^{mp}\) for robust motion control\(^{(10)}\). The block diagram of a 1-DOF (degree-of-freedom) robot system including DOB is shown in Fig. 1. In Fig. 1, \(g_{\text{dis}}, J, K, \theta^{\text{ref}}, \theta^{\text{g}}, \) and \(\tau^{\text{ext}}\) are cut-off frequency of a low-pass filter (LPF) in DOB, robot’s moment of inertia, torque coefficient, a position response value and an acceleration reference value, respectively. The subscript \(n\) denotes a nominal value, and \(s\) denotes a Laplace operator.

Fig. 2 shows the equivalent system of Fig. 1. By using DOB, disturbance torque is input to the system through a high-pass filter (HPF) equivalently as (1).

\[
\theta^{\text{ref}} = \frac{1}{J_n s^2} \left\{ J_n \theta^{\text{ext}} - \frac{s}{s + g_{\text{dis}}} \right\} \cdots \cdots \cdots \cdots (1)
\]

Ideal robust acceleration control is achieved, if \(s/(s + g_{\text{dis}}) \rightarrow 0, \ i.e. \ g_{\text{dis}} \rightarrow \infty\).

2.2 Reaction Torque Observer (RTOB) DOB is also utilized as the reaction torque observer (RTOB) for estimation of external torque\(^{(17)}\). While RTOB estimates wider bandwidth force information than force sensors, it requires identification of frictional torque in advance. By means of RTOB, estimated external torque \(\tau^{\text{ext}}\) is given by

\[
\tau^{\text{ext}} = \frac{g_{\text{react}}}{s + g_{\text{react}}} \tau^{\text{ext}}, \cdots \cdots \cdots \cdots (2)
\]

where \(\tau^{\text{ext}}\) is actual external torque and \(g_{\text{react}}\) is cut-off frequency of LPF in RTOB. Perfect torque estimation is achieved, if \(g_{\text{react}}/(s + g_{\text{react}}) \rightarrow 1, \ i.e. \ g_{\text{react}} \rightarrow \infty\). In the experiment of this research, external torque exerted on a robot is estimated by using not a force sensor but RTOB.
Perfect transparency is achieved if $T$ the slave side and the estimated external torque exerted on the master robot and the estimated external torque exerted on the slave robot, respectively. The external torques exerted on the robots $\tau_{\text{ext}}^s$ and $\tau_{\text{ext}}^m$ are estimated by using not force sensors but RTOBs. $T_1$ denotes delay time from the master side to the slave side and $T_2$ denotes delay time from the slave side to the master side. $C_1$, $C_4$, $C_5$, and $C_6$ are position control parameters, and $C_2$, $C_3$, $C_5$ and $C_6$ are force control parameters.

3. Analysis of Four-Channel and Three-Channel Architectures

In this section, the four-channel architecture shown in Section 2, the four-channel architecture with CDOB and the proposed three-channel architecture are analyzed by using hybrid matrices.

3.1 Hybrid Parameters

Fig. 4 shows network representation of teleoperation systems. Hybrid parameters $H_{11}$, $H_{12}$, $H_{21}$ and $H_{22}$ are defined as (3).

$$\begin{bmatrix} \tau_{\text{ext}}^m & -\theta_{\text{res}}^m \\ -\theta_{\text{res}}^m & s^2 \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \begin{bmatrix} \theta_{\text{res}}^e \\ -s \theta_{\text{res}}^e \end{bmatrix} \quad \quad (3)$$

Perfect transparency is achieved if $H_{11} = H_{22} = 0$ and $H_{12} = H_{21} = 1$. In this case, (4) and (5) are satisfied.

$$\begin{align*}
\tau_{\text{ext}}^m &= -\theta_{\text{res}}^m \\
\theta_{\text{res}}^m &= \theta_{\text{res}}^e 
\end{align*} \quad \quad (4, 5)$$

3.2 Conventional Four-Channel Architecture

The four-channel architecture shown in Fig. 3 is analyzed here. In this analysis, it is assumed that cut-off frequency of LPF in DOB and RTOB approaches infinity ($g_{\text{dis}} \to \infty$ and $g_{\text{res}} \to \infty$) and ideal robust acceleration control is achieved.

In Fig. 3, the bilateral system is expressed as (6) and (7), if DOB works ideally and disturbance torque including parameter fluctuation is suppressed completely, i.e. $\theta_{\text{res}}^m = \theta_{\text{res}}^e / s^2$ and $\theta_{\text{res}}^e = \theta_{\text{res}}^f / s^2$ are satisfied.

Here, the four-channel bilateral control system based on acceleration control is presented. In (6) and (7), control parameters are set as (8) and (9).

$$\begin{align*}
C_1 &= C_4 = C_m = C_s = C_p(s) \quad \quad (8) \\
C_2 &= C_3 = C_5 = C_6 = C_f \quad \quad (9)
\end{align*}$$

where $C_p(s) = K_p + K_s$ and $C_f$ are a position controller and a force controller, respectively. $K_p$, $K_s$ and $K_f$ denote position feedback gain, velocity feedback gain and force feedback gain, respectively. While PD control is implemented for position control, P control is implemented for force control. This is because differentiation of force response is too noisy for practical purposes.

From (6)–(8), master and slave acceleration reference values in the conventional four-channel architecture are calculated as (10) and (11).

$$\begin{align*}
\ddot{\theta}_{\text{ref}}^m &= C_p(s)(\dot{\theta}_{\text{ref}}^e e^{-T_1 s} - \dot{\theta}_{\text{ref}}^m) - C_f(\dot{\theta}_{\text{ref}}^m + \theta_{\text{ref}}^e e^{-T_1 s}) \\
\ddot{\theta}_{\text{ref}}^e &= C_p(s)(\dot{\theta}_{\text{ref}}^e e^{-T_1 s} - \dot{\theta}_{\text{ref}}^m) - C_f(\dot{\theta}_{\text{ref}}^m e^{-T_1 s} + \theta_{\text{ref}}^e) 
\end{align*} \quad \quad (10, 11)$$

Then, hybrid parameters can be calculated as (12)–(15), if the external torques are estimated precisely by means of RTOBs, i.e. $\tau_{\text{ext}}^m = \tau_{\text{ext}}^e$ and $\tau_{\text{ext}}^e = \tau_{\text{ext}}^s$ are satisfied. $T$ denotes round-trip delay time ($T = T_1 + T_2$).

$$\begin{align*}
H_{11} &= -s^2(2 + 2C_p(s)) + C_p(s)^2 e^{-T_1 s} - s \\ &= D(s) \\
H_{12} &= C_f(s^2 + 2C_p(s)) e^{-T_1 s} \\
H_{21} &= -C_f(s^2 + 2C_p(s)) e^{-T_1 s} \\
H_{22} &= C_f^2(e^{-T_1} - 1) \\
D(s) &= C_f \left[ s^2 + C_p(s)(1 + e^{-T_1}) \right] 
\end{align*} \quad \quad (12, 13, 14, 15)$$

If the system does not include communication time delay ($T_1 = T_2 = 0$), hybrid parameters are calculated as (17)–(20).

$$\begin{align*}
H_{11} &= -s^2 \\
H_{12} &= 1 \\
H_{21} &= -1 \\
H_{22} &= 0 
\end{align*} \quad \quad (17, 18, 19, 20)$$
Perfect transparency is achieved in the conventional four-channel architecture without time delay, if the force control parameter \( C_f \) is large enough.

### 3.3 Proposed Three-Channel Architecture

The proposed bilateral control system has three communication channels between master and slave robots. In concrete terms, this system has two transmission channels of position and force information from the master side to the slave side and one transmission channel of force information from the slave side to the master side. The master controller of the proposed three-channel teleoperation system does not include a position controller, i.e. only force control is implemented in the master side, in order to improve operability in the master side. In the proposed controller, models of a slave robot and communication time delay are not required differently from conventional methods such as the Smith predictor, CDOB and so on.

Here, control parameters in (6) and (7) are set as (21)–(23) differently from the four-channel architecture.

\[
C_1 = C_2 = C_p(s) \quad \cdots \quad (21)
\]

\[
C_4 = C_m = 0 \quad \cdots \quad (22)
\]

\[
C_2 = C_3 = C_5 = C_6 = C_f \quad \cdots \quad (23)
\]

In the proposed three-channel architecture, master and slave acceleration reference values are calculated as (24) and (25).

\[
\ddot{\theta}_m^{ref} = -C_f(\ddot{\theta}_m + \ddot{\theta}_s + e^{-T_{ds}}) \quad \cdots \quad (24)
\]

\[
\ddot{\theta}_s^{ref} = C_p(s)(\theta_m^{ref}e^{-T_{ds}} - \theta_s^{ref}) - C_f(\ddot{\theta}_m + e^{-T_{ds}} + \ddot{\theta}_s^{ref}) \quad \cdots \quad (25)
\]

Then, hybrid parameters can be calculated as (26)–(29), if the external torques are estimated precisely by means of RTOBs, i.e. \( \tau_m^{ext} = \ddot{\theta}_m^{ref} \) and \( \tau_s^{ext} = \ddot{\theta}_s^{ref} \) are satisfied.

\[
H_{11} = \frac{s^2}{C_f} \quad \cdots \quad (26)
\]

\[
H_{12} = e^{-T_{ds}} \quad \cdots \quad (27)
\]

\[
H_{21} = -e^{-T_{ds}} \quad \cdots \quad (28)
\]

\[
H_{22} = \frac{C_f(e^{-T_{ds}} - 1)}{s^2 + C_p(s)} \quad \cdots \quad (29)
\]

If the system does not include communication time delay \((T_1 = T_2 = 0)\), hybrid parameters are calculated as (30)–(33).

\[
H_{11} = \frac{s^2}{C_f} \quad \cdots \quad (30)
\]

\[
H_{12} = 1 \quad \cdots \quad (31)
\]

\[
H_{21} = -1 \quad \cdots \quad (32)
\]

\[
H_{22} = 0 \quad \cdots \quad (33)
\]

Perfect transparency is also achieved in the proposed three-channel architecture without time delay, if the force control parameter \( C_f \) is large enough in the same way as the case of the conventional four-channel architecture.

### 3.4 Discussion of Architectures with Time Delay

In case that the systems include communication time delay, all hybrid parameters are functions of a Laplace operator \( s \). Therefore, hybrid parameters of the proposed three-channel architecture with time delay are compared with those of the conventional four-channel architecture by using Bode diagrams. Fig. 5–Fig. 8 show gain characteristics of hybrid parameters \( H_{11}, H_{12}, H_{21} \) and \( H_{22} \), respectively. Control parameters are set to \( C_p(s) = 400 + 40s \) and \( C_f = 3 \). Delay time is set to \( T_1 = T_2 = 100 \) [ms] (constant value). In these figures, hybrid parameters of the conventional four-channel architecture with/without CDOB (11) and the proposed three-channel architecture are plotted.

Here, the computation of hybrid parameters in the conventional four-channel architecture with CDOB is described as a guide. In the conventional four-channel architecture with CDOB, master and slave acceleration reference values are...
calculated as (34) and (35)

$$\dot{\theta}_m^{ref} = C_p(s)(\theta_s^{ref} e^{-T_1 s} - \dot{\theta}_d^{ref}) - C_f(\dot{\theta}_m^{ref} + \dot{\theta}_m^{est} e^{-T_2 s})$$

$$= C_p(s)(\theta_s^{ref} e^{-T_1 s} - \dot{\theta}_d^{ref}) - C_f(\dot{\theta}_m^{est} + \dot{\theta}_m^{est} e^{-T_2 s})$$

$$\dot{\theta}_s^{ext} = C_p(s)(\theta_s^{ref} e^{-T_1 s} - \dot{\theta}_d^{ref}) - C_f(\dot{\theta}_m^{est} + \dot{\theta}_m^{est} e^{-T_2 s})$$

(34)

$$\dot{\theta}_s^{ext} = C_p(s)(\theta_s^{ref} e^{-T_1 s} - \dot{\theta}_d^{ref}) - C_f(\dot{\theta}_m^{est} + \dot{\theta}_m^{est} e^{-T_2 s})$$

(35)

where $\dot{\theta}_d^{ref} = \theta_s^{ref} e^{-T_1 s} - \dot{\theta}_s^{ref} e^{-T_2 s}$ denotes a compensation value output from CDOB (42).

Then, hybrid parameters of the conventional four-channel architecture with CDOB can be calculated as (36)–(39), if the external torques are estimated precisely by means of RTOBs, i.e. $\dot{\theta}_m^{ext} = \dot{\theta}_m^{est}$ and $\dot{\theta}_s^{ext} = \dot{\theta}_s^{est}$ are satisfied.

$$H_{11} = \frac{s^2}{C_f}$$

(36)

$$H_{12} = \frac{C_f(s^2 + C_p(s)) e^{-T_2 s} + C_p(s) e^{-T_1 s}}{D(s)}$$

(37)

$$H_{21} = -e^{-T_1 s}$$

(38)

$$H_{22} = \frac{C_f e^{-T_1 s} - 1}{D(s)}$$

(39)

$$D(s) = C_f \left[ s^2 + 2C_p(s) \right]$$

(40)

In Fig. 5, it is shown that the gain characteristics of the proposed three-channel architecture and the conventional four-channel architecture with CDOB are not affected by time delay. However, they have large gains in high-frequency area. Thus, the force control parameter $C_f$ has to be set to a larger value to suppress the gains of $H_{11}$. Both in Fig. 6 and in Fig. 7, it is shown that the gain characteristics of the proposed three-channel architecture are zero in all-frequency area. Therefore, the proposed three-channel architecture satisfies the condition $|H_{12}| = |H_{21}| = 1$ (0 dB), while the other architectures do not satisfy the condition. In Fig. 8, all three kinds of architectures have quite small gains in all-frequency area. The condition $|H_{22}| = 0$ is almost satisfied by using every architecture discussed in this section. The position control parameter $C_p(s)$ has to be set to a larger value to suppress the gains of $H_{22}$. 

4. Experiment

In this section, experimental results are shown to confirm the validity of the proposed three-channel architecture in bilateral teleoperation with time delay.

4.1 Experimental Setup

The experiments are performed by using 1-DOF master and slave manipulators shown in Fig. 9. In the experiments, the slave manipulator had contact with aluminum rod in contact motion. Parameters utilized in the experiments are listed in Table 1.

4.2 Experimental Results

Fig. 10–Fig. 12 show experimental results with time delay in the case using the four-channel architecture without CDOB, the four-channel architecture with CDOB, and the proposed three-channel architecture, respectively. Virtual and randomly-fluctuating communication time delay ($50 \text{[ms]} \leq T_1, T_2 \leq 150 \text{[ms]}$) was simulated on a computer. In Fig. 10(b), Fig. 11(b) and Fig. 12(b), the master force responses multiplied by $(-1)$ are plotted to compare the master responses with the slave responses.

In Fig. 10(a), it is shown that the position responses of the master and slave robots almost perfectly tracked each other. However, the operator felt large manipulating force in free motion as shown in Fig. 10(b). This is because the master and slave robots tried to track each other, although the communication lines between the master and slave sides had time delay elements. Especially in free motion, it was true that the position responses of the master and slave robots almost perfectly tracked each other, but the operator could not manipulate the master robot so quickly because of the large manipulating force. Therefore, the conventional four-channel architecture without CDOB generated the large manipulating force in free motion.

In Fig. 11(a), it is shown that the position responses of the master and slave robots almost perfectly tracked each other. In addition, the operator did not feel large manipulating force.

Table 1. Parameters in experiments

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal moment of inertia</td>
<td>100 kgfcm</td>
</tr>
<tr>
<td>Nominal torque constant</td>
<td>0.156 Nm/A</td>
</tr>
<tr>
<td>Position feedback gain</td>
<td>0.156</td>
</tr>
<tr>
<td>Velocity feedback gain</td>
<td>0.156</td>
</tr>
<tr>
<td>Force feedback gain</td>
<td>0.156</td>
</tr>
<tr>
<td>Cut-off frequency of DOB</td>
<td>0.156</td>
</tr>
<tr>
<td>Cut-off frequency of RTOB</td>
<td>0.156</td>
</tr>
<tr>
<td>Control period</td>
<td>0.156 ms</td>
</tr>
</tbody>
</table>

![Fig. 9. 1-DOF master and slave manipulators](image)

![Fig. 10. Experimental results (conventional four-channel architecture without CDOB)](image)
motion was achieved at the same level as conventional methods. However, perfect transparency was not achieved differently from the previous analysis using hybrid parameters. This is because cut-off frequency of LPF in DOB and RTOB was set to 200 rad/s in the experiment, while it was assumed in the analysis that ideal acceleration control ($g_{obs} \rightarrow \infty$) and ideal force estimation ($g_{rea} \rightarrow \infty$) were achieved. The proposed three-channel architecture achieved precise force feedback to the extent possible both in free motion and in contact motion. The validity of the proposed three-channel architecture was confirmed by the experimental results.

5. Conclusions

In this paper, a novel architecture for bilateral teleoperation was proposed. The proposed bilateral control system has three communication channels with without time delay, and the master controller does not include a position controller. The transmission characteristics of force and position information between master and slave robots were clarified in the analysis using hybrid parameters. In the experiment, it was shown that the three-channel architecture with time delay gave better performance than the other conventional methods.

As future works, stability analysis of the proposed three-channel architecture has to be performed firstly. Then the control bandwidth should be brought close to the ideal conditions ($g_{obs}, g_{rea} \rightarrow \infty$) to a maximum extent.

References


Ryogo Kubo (Member) received the B.E. degree in system design engineering and the M.E. degree in integrated design engineering from Keio University, Yokohama, Japan, in 2005 and 2007, respectively. In 2007, he joined Nippon Telegraph and Telephone (NTT) Corporation. He is currently engaged in research and development of optical access networks and systems at NTT Access Network Service Systems Laboratories, Chiba, Japan. He is a Member of the IEEJ, the Society of Instrument and Control Engineers (SICE) and the Institute of Electronics, Information and Communication Engineers (IEICE).

Noriko Iiyama (Student Member) received the B.E. degree in system design engineering from Keio University, Yokohama, Japan, in 2006. She is currently working toward the M.E. degree in integrated design engineering at Keio University. Her research interests include robotics, motion control and haptics.

Kenji Natori (Student Member) received the B.E. degree in system design engineering and the M.E. degree in integrated design engineering from Keio University, Yokohama, Japan, in 2004 and 2006, respectively. He is currently working toward the Ph.D. degree at Keio University. From April 2007, he is a Research Fellow of the Japan Society for the Promotion of Science (JSPS). His research interests include time delay systems, bilateral control and network-based control systems (NBCS). He is a Student Member of the IEEE.

Kouhei Ohnishi (Senior Member) received the B.E., M.E., and Ph.D. degrees in electrical engineering from the University of Tokyo, Tokyo, Japan, in 1975, 1977 and 1980, respectively. Since 1980, he has been with Keio University, Yokohama, Japan. His research interests include mechatronics, motion control, robotics and haptics. Prof. Ohnishi received Best Paper Awards from the IEEJ and the Japan Society for Precision Engineering, and Outstanding Paper Awards at IECON’85, IECON’92, IECON’93 and IECON’05. He also received the EPE-PEMC Council Award and the Dr.-Ing. Eugene Mittelmann Achievement Award from the IEEE Industrial Electronics Society in 2004. He is a Fellow of the IEEE.

Hirotaka Furukawa (Non-member) received the B.E. and M.E. degrees in applied physics and chemistry from the University of Electro-Communications, Tokyo, Japan, in 2001 and 2003, respectively. Since 2003, he has been with NTT DoCoMo, Inc. He is currently a development engineer at Communication Device Development Department, Kanagawa, Japan.