Admittance-based Bilateral Control System
Implementing Communication Traffic Reduction Method

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Abstract

Robotic teleoperation with haptic feedback has gained attention and has been studied extensively in recent years. A bilateral control system is one of the methods to realize transmission of tactile sense from a remote place to an operator. One of the major systems of the bilateral control system is an acceleration-based four-channel bilateral control (ABC) system, which is one of the transparent systems. However, the ABC system transmits large data, position and force information, and/or its derivative value of the master and slave system. This paper proposes a novel admittance-based bilateral control system using only two communication channels without deteriorating the control performance, which results in communication data reduction. Besides, we apply a prediction-based data reduction method to the proposed system for communication frequency reduction. The validity of the proposed system is confirmed by experiments. The obtained results show the proposed system needs smaller data and lower communication frequency to realize transmission of tactile sense.

Keywords: bilateral control, force control, admittance control, Traffic reduction.

1. Introduction

Robotic teleoperation technologies allow humans to work in remote areas, such as space, the deep sea, nuclear plants, and so on. In particular, teleoperation with haptic feedback enables humans to perform delicate tasks intuitively and behave as if operators are in remote areas. A bilateral control system is one of the effective methods to realize teleoperation with haptic feedback. The bilateral control system consists of two robot systems, a master (local) robot, which is operated by a human, and a slave (remote) robot, which works in remote areas.

Many types of bilateral control systems have been studied so far. For instance, a position symmetric-type bilateral control system communicates the position information between master and slave system. Force reflecting-type bilateral control system transmits position information from master to slave and the force information from slave to master. These systems are called two-channel systems since these systems have two communication lines. Hannaford applied an equivalent circuit model to bilateral control systems to formulate the relationship between master and slave (1). Lawrence proposed as an index “transparency” and indicated transparent system needs velocity and force components of master and slave where the system has four communication lines (2). Iida et al. improved a four-channel bilateral control system and proposed acceleration-based bilateral control (ABC) system, which is one of the transparent systems. Moreover, Iida et al. proposed the two indices, “reproducibility”, which shows how precisely the environmental impedance is reproduced in the master side and “operationality”, which shows how smoothly the operator manipulates the master robot (3).

However, a highly transparent system like acceleration-based four-channel bilateral control needs larger data than other systems. To reduce the transmitted haptic data, a novel 2ch system, which has the same performance as the 4ch system has been proposed recently (6,7,8).

Another problem in the communication field for practical use is that transmission of vivid haptic sensation needs high communication frequency between master and slave. To reduce the communication frequency of bilateral control, the prediction-based approach is one of the major methods (6,7,8).

This paper proposes the novel admittance-based two-channel control architecture implementing the prediction-
based approach for haptic data reduction and communication frequency reduction. The validity of the proposed system is confirmed by experiments.

The rest of this paper is organized as follows. Chapter 2 explains the conventional acceleration-based 4ch bilateral control and the proposed system and analyzes the control performance of both systems. In chapter 3, a prediction-based approach for lower communication frequency. In chapter 4, experimental results are shown. Finally, this paper concludes in chapter 5.

2. Bilateral Control

2.1 Disturbance Observer

In this study, the disturbance observer\(^{(9)}\) (DOB) shown in Fig. 1 was applied to eliminate disturbance where \(x, f, M, s, Q_{DOB}\). \(f^{DOB}\) denote the position, force, mass, the Laplace operator, low-pass filter, disturbance estimated by DOB, respectively. The subscript ref, n, dis, and res represent reference, nominal, disturbance, and response. The acceleration response is expressed as

\[
s^2x_{\text{res}} = \frac{M_n s^2 x_{\text{ref}} - (1 - Q_{DOB}) f_{\text{dis}}}{(1 - Q_{DOB})M + Q_{DOB}M_n} \tag{1}
\]

where assuming the cut-off frequency of DOB is large enough to be considered as \(Q_{DOB} \approx 1\), the acceleration response coincides with acceleration reference and the controlled plant is nominalized. The DOB is also utilized as a reaction force observer (RFOB) for the reaction force estimation\(^{(10)}\). In this paper, the reaction force is estimated by RFOB.

2.2 Acceleration-based Bilateral Control System

The bilateral control system has two control goals. The first goal is position synchronization between master and slave. The other one is the realization of “the law of action and reaction”. These two goals are expressed as

\[
x_1 - x_2 = 0 \tag{2}
\]

\[
f_1 + f_2 = 0 \tag{3}
\]

where \(f\) denotes force and the subscript 1 and 2 represent master and slave. These control goals are achieved by using modal transformation. The acceleration references are finally expressed as

\[
s^2x_{\text{ref}} = -K_p(x_1 - x_2) - K_v(sx_1 - sx_2) - C_f(f_1 + f_2) \tag{4}
\]

\[
s^2x_{\text{ref}} = -K_p(x_2 - x_1) - K_v(sx_2 - sx_1) - C_f(f_2 + f_1) \tag{5}
\]

where \(K_p, K_v\), and \(K_f\) denote the position, velocity, and force feedback gain. In this paper, a PD controller is used for position control and a P controller is used for force controller.
The whole system is shown in Fig. 2.

The relation between master and slave of position and force can be formulated by hybrid parameters $H$ expressed as

$$[f_1] = [H_{11} \ H_{12}] \ [x_1 \ -f_2].$$

The relation between position and force on the slave side is expressed as

$$f_2 = Z_e x_2$$

where $Z_e$ denotes environmental impedance. From (4), (5), and (6), the relation between position and force on the master side is expressed as

$$f_1 = \left( \frac{-H_{12}}{H_{21} - H_{22} Z_e} Z_e + \frac{H_{11}}{H_{21} - H_{22} Z_e} \right) Z_e$$

$$= (P_1 Z_e + P_o) x_1$$

where $P_1$ and $P_o$ denote reproducibility and operationality. If $P_1 = 1$ and $P_o = 0$ are realized, an operator can feel the environmental impedance precisely. The hybrid parameters of the ABC system are expressed as

$$H_{11}^{4ch} = -\frac{s^2}{C_p G_{hpf}} \left( 1 - \frac{C_p G_{hpf}}{M C_l G_{hpf} (s^2 + 2C_p) + C_p G_{hpf}} \right)$$

$$H_{12}^{4ch} = 1 + \frac{M C_l G_{hpf} (s^2 + 2C_p) + C_p G_{hpf}}{C_p G_{hpf}}$$

$$H_{21}^{4ch} = 1 + \frac{M C_l G_{hpf} (s^2 + 2C_p) + C_p G_{hpf}}{C_p G_{hpf}}$$

$$H_{22}^{4ch} = -\frac{G_{hpf}}{M C_p} \left( 1 - \frac{M C_l G_{hpf} s^2}{M C_l G_{hpf} (s^2 + 2C_p) + C_p G_{hpf}} \right)$$

### 2.3 Proposed bilateral control system

The proposed system is shown in Fig. 3 where $Y$ and $s^2 x_{2 \rightarrow 1}^{cmd}$ denote the arbitrary admittance and acceleration command value from slave to master. The proposed system transmits the force from master to slave and acceleration command from slave to master and has only two communication channels.

The acceleration references are finally expressed as

$$s^2 x_{1 \rightarrow 1}^{ref} = s^2 x_{2 \rightarrow 1}^{cmd} - (K_p x_1 + s x_1 K_v)$$

$$s^2 x_{2}^{ref} = -Y \left( 1 + \frac{K_v}{s} + \frac{K_p}{s^2} \right) (f_2 + f_3) - \left( K_p x_2 + s x_2 K_v \right).$$

From (6), (13), and (14), the hybrid parameters of the proposed system are expressed as

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### Table 1. Parameters for simulations and experiments.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Meaning</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_p$</td>
<td>Position feedback gain</td>
<td>3600 1/s²</td>
</tr>
<tr>
<td>$K_v$</td>
<td>Velocity feedback gain</td>
<td>120 1/s</td>
</tr>
<tr>
<td>$K_t/Y$</td>
<td>Force feedback gain/virtual admittance</td>
<td>5.0 kg⁻¹</td>
</tr>
<tr>
<td>$M$</td>
<td>Master/slave mass</td>
<td>0.2 kg</td>
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<tr>
<td></td>
<td>Cutoff frequency of DOB</td>
<td>300 rad/s</td>
</tr>
<tr>
<td></td>
<td>Cutoff frequency of RFOB</td>
<td>300 rad/s</td>
</tr>
<tr>
<td></td>
<td>Sampling time</td>
<td>0.2 ms</td>
</tr>
</tbody>
</table>

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Environment impedance 10000 + 10s
Operationality, reproducibility, and transparency of the proposed admittance architecture are compared with those of the conventional ABC system using bode diagrams. Parameters utilized in simulations are listed in Table 1. Fig. 4 shows the gain characteristics of operationality, reproducibility, and transparency of the ABC system and the proposed system. Fig. 4 shows that in a low-frequency area, the operationality of the ABC system is almost the same as that of the proposed system. Figs. 4(b) and 4(c) show the proposed system achieves better performance than the ABC system although the proposed system has only two communication channels.

\[ H_{11}^{\text{prop}} = \frac{s^2}{C_f G_{lpf}} \]  \hspace{1cm} (15)

\[ H_{12}^{\text{prop}} = 1 + \frac{C_p G_{hpf} s^2}{M C_f G_{lpf} (s^2 + 2 C_p)} \]  \hspace{1cm} (16)

\[ H_{21}^{\text{prop}} = 1 + \frac{C_p G_{hpf} s^2}{M C_f G_{lpf} (s^2 + 2 C_p)} \]  \hspace{1cm} (17)

\[ H_{22}^{\text{prop}} = G_{hpf} \frac{2 C_f G_{lpf} M (s^2 + 2 C_p) + G_{hpf} s^2}{C_f G_{lpf} M^2 (s^2 + 2 C_p)} \]  \hspace{1cm} (18)

2.4 Comparison

Operationality, reproducibility, and transparency of the proposed admittance architecture are compared with those of the conventional ABC system using bode diagrams. Parameters utilized in simulations are listed in Table 1. Fig. 4 shows the gain characteristics of operationality, reproducibility, and transparency of the ABC system and the proposed system. Fig. 4 shows that in a low-frequency area, the operatinality of the ABC system is almost the same as that of the proposed system. Figs. 4(b) and 4(c) show the proposed system achieves better performance than the ABC system although the proposed system has only two communication channels.

2.5 Experiments

Experiments were conducted to confirm the validity of the proposed architecture. The experimental setup is shown in Fig. 5. Two linear motors were used as the master robot and slave robot. The slave robot was contacted with an aluminum block. For comparison, the master robot was operated by a linear motor to perform the same motion in both systems. The parameters used in the experiments are listed in Table 1. Figs. 6 and 7 show the position and the force response of the ABC system and the proposed system. The obtained results show the transmission of haptic sensation is realized by two communication channels.

3. Communication Traffic Reduction

In this chapter, the prediction-based communication traffic reduction is realized in the previously proposed method. For simplicity, force transmission from master to slave is only explained although this method is implemented in both master and slave side. In this approach, the master system needs to transmit force information if the predicted master force on the slave side exceeds the predefined threshold from real observed information on the master side. The future received data is predicted in both the master and
the slave side.

### 3.1 Prediction method by using past time series data

In this paper, two types of prediction, zero-order hold (ZOH) and first-order hold (FOH), are used. The predicted value with zero-order hold and first-order hold is expressed as

\[ f_2^{pr} [k] = \begin{cases} f_1[k_T], & \text{(ZOH)} \\ f_1[k_T] + \sum_{i=1}^{k-k_T} \dot{f}_1 [k_T] \delta t, & \text{(FOH)} \end{cases} \tag{19} \]

where \( f_2^{pr} \), \( k \), \( k_T \), \( k_R \) and \( \delta t \) denote predicted master force in slave side, current time, the last time when the master transmitted to the slave, the last time when the slave received data from the master, and sampling time. Thus, in this case, the acceleration reference of the slave is expressed as

\[ s^2 x_2^{ref} = -y \left( 1 + \frac{K_v}{S} + \frac{K_p}{S^2} \right) (f_2 + f_2^{pr}) \]

\[ - (K_p x_2 + s x_3 K_v). \]  \tag{20} \]

On the other hand, the predicted master force in slave side is estimated in master side expressed as

\[ f_1^{\hat{pr}} [k] = \begin{cases} f_1[k_T], & \text{(ZOH)} \\ f_1[k_T] + \sum_{i=1}^{k-k_T} \dot{f}_1 [k_T] \delta t, & \text{(FOH)} \end{cases} \]

where \( f_2^{pr} \) is the estimated value on the master side which is predicted on the slave side. If the error between \( f_2^{pr} \) and \( f_2^{pr} \) exceeds the predefined threshold, communication between master and slave starts.

### 3.2 Differentiation of force information

From (20) and (22), the predicted value and the estimated value of the predicted value needs differentiation of force information, which includes much noise. To reduce the noise effect, the low pass filter and the least-squares method is utilized. The relationship between time and force is approximated as a first-order function expressed as

\[ y = ax + b \]  \tag{22} \]

where \( y \), \( a \), \( x \), and \( b \) denote force information, the gradient, time, and \( y \)-intercept. To determine the \( a \) and \( b \) from the given data set \((x_i, y_i)\), an evaluation function is utilized. The evaluation function \( J \) is expressed as

\[ J = \sum_{i=1}^{N} \left( y_i - (ax_i + b) \right)^2 \]  \tag{23} \]

where \( N \) is the window size. \( a \) and \( b \) are determined to minimize the evaluation function \( J \). As a result, \( \dot{f}_1 \) is calculated as
\[ f_i[k] = a[k]. \]  

### 3.3 Model Selection Based on AIC

This section explains the model selection based on an Akaike information criterion (AIC\(^{(1)}\)). The AIC is a statistical index of model selection. The AIC value is defined as

\[ \text{AIC} = -2l + 2m \]  

where \( l \) and \( m \) denote the maximum logarithmic likelihood and the number of parameters. The preferred model is the one with a minimum AIC value. When the prediction error is assumed to follow the normal distribution, the probability density function \( f \) is expressed as

\[ f(y; \mu, \sigma) = \frac{1}{\sqrt{2\pi \sigma^2}} \exp\left(-\frac{(y - \mu)^2}{2\sigma^2}\right) \]  

where \( y \), \( \mu \), and \( \sigma^2 \) denote the regression equation, the average value, and the variance value. This paper only explains the first order regression expressed as

\[ y = ax + b. \]  

The logarithmic likelihood value for a given data set \((x_i, y_i)\) is expressed as

\[ l(a, b, \sigma) = \ln \left( \prod_{i=1}^{N} \frac{1}{\sqrt{2\pi \sigma^2}} \exp\left(-\frac{(y_i - \mu)^2}{2\sigma^2}\right) \right) \]

\[ = \frac{1}{\sqrt{2\pi \sigma^2}} \sum_{i=1}^{N} (y_i - (ax_i + b))^2 - n \ln \left( \sqrt{2\pi \sigma^2} \right) \]  

The parameters \( a, b, \sigma \) for maximizing (28) is calculated as

\[ \begin{bmatrix} \hat{a} \\ \hat{b} \end{bmatrix} = \left[ \begin{array}{cc} \sum_{i=1}^{N} x_i^2 & \sum_{i=1}^{N} x_i \\ \sum_{i=1}^{N} x_i & N \end{array} \right]^{-1} \left[ \begin{array}{c} \sum_{i=1}^{N} x_i y_i \\ \sum_{i=1}^{N} y_i \end{array} \right] \]  

\[ \sigma^2 = \frac{\sum_{i=1}^{N} (y_i - (\hat{a}x_i + \hat{b}))^2}{N} \]  

From (29) and (30), the AIC value is calculated as

\[ \text{AIC}(1) = -2l(\hat{a}, \hat{b}, \hat{\sigma}) + 6. \]  

AIC(0) is also similarly calculated. The prediction models, ZOH and FOH, are selected as

\[ f_2^{\text{pr}}[k] = \begin{cases} f_2[k_T] & (\text{AIC}(0) < \text{AIC}(1)) \\ f_2[k_T] + \sum_{i=1}^{k-k_R} f_1[k_T] \delta t & (\text{AIC}(1) < \text{AIC}(0)). \end{cases} \]  

### 4. Experiments

The experimental setup is shown in Fig. 5. The parameters utilized in experiments are listed in Table 2. The experiments were conducted to confirm the validity of the
This paper applied the prediction-based haptic data reduction approach to the proposed system for aiming for practical use. The obtained results show the effectiveness of the proposed method. As future work, the analysis of the effect of window size for LMS and the predefined threshold value is expected to be conducted. Moreover, other prediction models need to be considered since this paper only utilized zero and first order-based prediction.

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