Central Controller for Hybrid Control over Network

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***Abstract*— In this paper, a central controller for position/force hybrid control over network is proposed. In the proposed method, the central controller receives position and force information from each plant. Then, the central controller generates acceleration references for each plant by using a hybrid controller and a dead time compensator. As an application, bilateral control with communication delay is implemented. And some simulations and experiments verify the validity of the proposed method.**

I. Introduction

A position/force hybrid control is very important to control robots that contact with environments. For example, a processing of products in plant requires a high precise hybrid control. The hybrid control is also required for a bilateral control and a multilateral control [1], [2]. The bilateral control requires two control targets. The first is that a slave robot tracks a master robot. The second is that an external force added to a master robot is equal to an external force added to a slave one.

Raibert established a basic theory for a hybrid control [3]. Khatib improved this theory. He defined an equivalent mass matrix to treat both of an acceleration reference of a position control and a force reference of a force control in the same dimension [4]. Morisawa *et al.* described a task of robots as a mode [5]. Kubo *et al.* generalized this method by using discrete Fourier transform (DFT) [6]. However, the mode is hardly used for a hybrid control system with multiple plants that are connected through network with communication delay. The reason comes from the fact that it is difficult to observe the mode, because each plant sends and receives position/force information each other with communication delay. For example, a bilateral control has two plants and two modes. One mode is a difference in the position between a master robot and a slave one. The other mode is a total value of an external force added to the master robot plus an external force added to the slave one. Each mode should be equal to 0 ideally. However, it is impossible to observe these modes at the master side or the slave side, when there exists communication delay between the master side and the slave side.

For the reason listed above, the mode is hardly used for a hybrid control over network. Instead, many researchers have used a hybrid matrix[7] as a control goal, although there are a lot of researches about a hybrid control over network. For example, Anderson *et al.* derived a scattering matrix from the hybrid matrix to discriminate passivity of a hybrid control system over network [8]. Niemeyer *et al.* applied wave variables to communication lines to stabilize a network [9]. Some researches use a dead time compensator to compensate communication delay [10]. Small gain theorem is also utilized to stabilize the system [11]. However, each approach does not provide satisfactory performance. This means that the hybrid matrix is not suitable for the design of a hybrid control system over network.

In this paper, a novel structure for a hybrid control over network is proposed. This structure makes it possible to control the mode. This structure does not transmit position/force information directly between some plants. Instead, position/force information is transmitted to a central controller. The central controller estimates modes from received position/force information. Then this controller generates acceleration references that are transmitted to plants. An acceleration control is implemented at the each plant using this acceleration reference. Although there exists communication delay between each plant and the central controller, communication disturbance observer (CDOB)[12], [13] make it possible to estimate modes and stabilize the system. As an application, a bilateral control with communication delay is implemented in this paper. And some simulations and experiments verify the validity of the proposed method.

This paper is organized as follows. In Section 2, a conventional hybrid control using the concept of the mode is explained. Then, in Section 3, the structure for a hybrid control over network is proposed. Some simulations and experiments verify the validity of the proposed structure in Section 4 and 5, respectively. Finally, Section 6 concludes this paper.

II. Hybrid Control

In this section, at first, robust acceleration control using a disturbance observer (DOB) is presented [14][15]. Secondly, a conventional hybrid control using the concept of the mode is explained [16].

A. Robust Acceleration Control using Disturbance Observer

The block diagram of robust acceleration control using DOB is shown in Fig. 1. In Fig. 1, $\ddot{x}^{ref}(t)$, $\dot{x}(t)$, $\ddot{x}(t)$, $I_a^{ref}(t)$, $f^{ext}(t)$ and $\hat{f}^{dis}(t)$ mean an acceleration reference, a velocity response, an acceleration response, a current reference, an external force added to a robot and a disturbance force estimated by DOB, respectively. In addition, M, K_t, g_{dob} and s means mass of a robot, thrust coefficient of a motor, cut-off frequency of a low pass filter and a Laplace operator, respectively. Where a suffix n means a nominal value. A

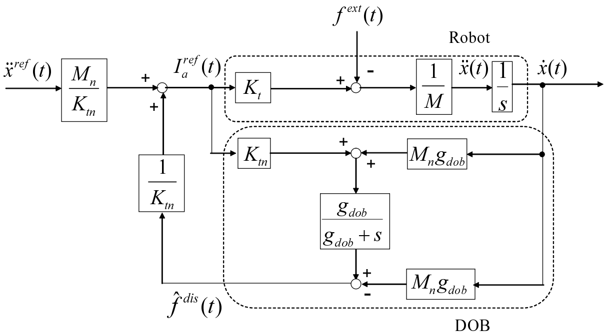


Fig. 1. A robust acceleration control using DOB

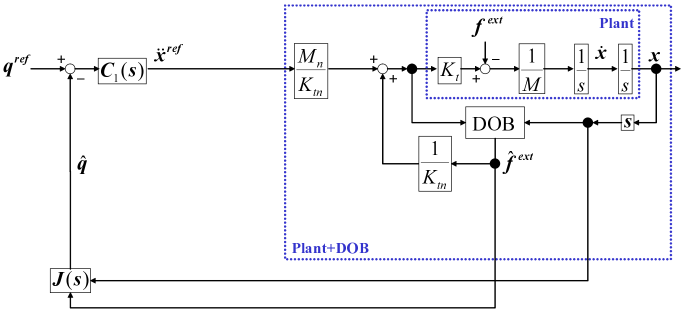


Fig. 2. A block diagram of a position/force hybrid control system

disturbance force $f^{dis}(t)$ contains $f^{ext}(t)$, a frictional force $D\dot{x}(t)$, modeling errors $\Delta M := M - M_n$, $\Delta K_t := K_{tn} - K_t$ and so on. $f^{dis}(t)$ is described as (1).

$$f^{dis}(t) = f^{ext}(t) + \Delta M \ddot{x}(t) + \Delta K_t I_a^{ref}(t) + D\dot{x}(t) \tag{1}$$

Relationship between $\hat{f}^{dis}(t)$ and $f^{dis}(t)$ is obtained as (2).

$$\hat{f}^{dis}(t) = G_T f^{dis}(t) = \frac{g_{dob}}{s + g_{dob}} f^{dis}(t) \tag{2}$$

If $D\dot{x}(t)$, M and K_t are known values, we can estimate $f^{ext}(t)$. Therefore, DOB often used as a reaction force observer (RFOB). In this paper, we use single-degree-of-freedom robots with litte frictional force for experiment. So $D\dot{x}(t)$ is ignored. In addition, we assume ΔM and ΔK_t are 0. Therefore, $\hat{f}^{dis}(t)$ is used as $\hat{f}^{ext}(t)$ as (3).

$$\hat{f}^{dis}(t) = \hat{f}^{ext}(t) \tag{3}$$

B. Position/force Hybrid Control

Fig. 2 shows a conventional hybrid control system using the concept of the mode. $\boldsymbol{q^{ref}}$ and $\hat{\boldsymbol{q}}$ denote a modal reference vector and an estimated modal vector. $\hat{\boldsymbol{q}}$ is calculated at a transformation matrix $\boldsymbol{J(s)}$ by a position vector $\boldsymbol{x} = [x_1, x_2, ..., x_n]^T$ and a force vector $\hat{\boldsymbol{f}}^{\boldsymbol{ext}} = [\hat{f}_1^{ext}, \hat{f}_2^{ext}, ..., \hat{f}_n^{ext}]^T$ at the plant. An acceleration response vector $\ddot{\boldsymbol{x}}^{\boldsymbol{ref}} = [\ddot{x}_1^{ref}, \ddot{x}_2^{ref}, ..., \ddot{x}_n^{ref}]^T$, that is applied to the plant, is calculated at a controller $\boldsymbol{C_1(s)}$. DOB is utilized to compensate $\boldsymbol{f^{ext}}$.

If the hybrid control system consists of multiple plants, $\ddot{x}_i^{ref}$(i=0, 1, ..., n) is calculated at each plant as shown in

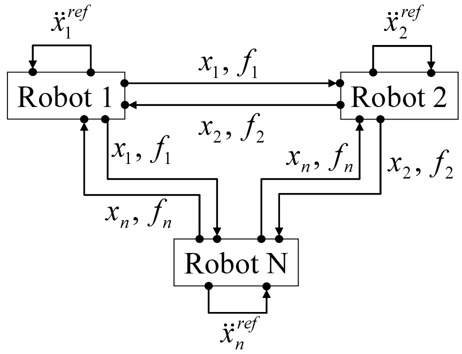


Fig. 3. The conventional structure for a hybrid control system with multiple plants

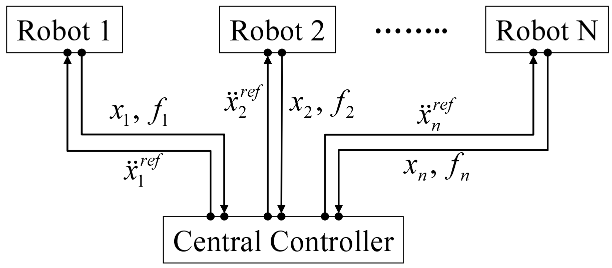


Fig. 4. The proposed structure for a hybrid control system with multiple plants

Fig. 3. The position and force are transmitted between each plant.

III. Hybrid Control over Network

A. Proposed position/force hybrid control

The mode is hardly used for a hybrid control system with multiple plants that are connected through network with communication delay. The reason comes from the fact that it is difficult to observe the mode, because each plant sends and receives position/force information each other with communication delay. But the proposed structure, that is shown in Fig. 4, makes it possible to observe the mode. In the proposed structure, $\ddot{x}_i^{ref}$ is calculated at a central controller. All position and force are sent to the central controller in order to calculate $\ddot{x}_i^{ref}$. Then, $\ddot{x}_i^{ref}$ is sent to each plant.

A block diagram of a proposed position/force hybrid control system is shown in Fig. 5. The central controller and the plants are connected through network. $\boldsymbol{E(s)}$ denotes the communication delay between the central controller and the plants. In the central controller side, a communication disturbance observer (CDOB)[13] is utilized to estimate $\boldsymbol{x}$. The estimated position vector $\hat{\boldsymbol{x}}$ is calculated from $\ddot{\boldsymbol{x}}^{\boldsymbol{ref}}$ and $\boldsymbol{x}$ that is sent from the plants with communication delay. In the plants side, a convergence term $C_2(s)$ is inserted. This part has an effect to reduce a steady-state error between $\boldsymbol{x}$ and $\hat{\boldsymbol{x}}$ [12].

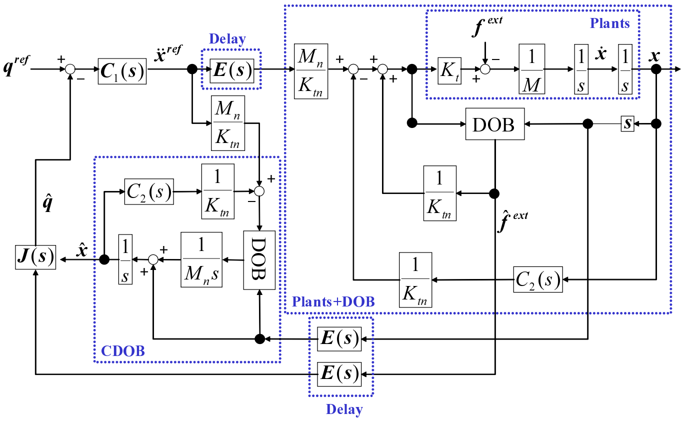


Fig. 5. A block diagram of a proposed position/force hybrid control system

B. Application

A bilateral control system over network is designed as an example of the application of the proposed hybrid control. The bilateral control system consists of two robots : a manually operated master robot and a slave robot that establishes contact with a remote environment. Position and force are transmitted between the master robot and the slave one over a network. $x_m(t)$, x_s(t), $f_m^{ext}(t)$ and, $f_s^{ext}(t)$ are defined as a position of the master, a position of the slave, an external force applied on the master and, an external force applied on the slave, respectively. $\boldsymbol{x}$ and $\boldsymbol{f^{ext}}$ are obtained as (4) and (5), respectively.

$$\boldsymbol{x} = \begin{bmatrix} x_m(t) \\ x_s(t) \end{bmatrix} \tag{4}$$

$$\boldsymbol{f^{ext}} = \begin{bmatrix} f_m^{ext}(t) \\ f_s^{ext}(t) \end{bmatrix} \tag{5}$$

$\boldsymbol{q^{ref}}$ is given by (6).

$$\boldsymbol{q^{ref}} = \begin{bmatrix} x_m(t) - x_s(t) \to 0 \\ f_m(t) + f_s(t) \to 0 \end{bmatrix} \tag{6}$$

$x_m(t) - x_s(t)$ and $f_m(t) + f_s(t)$ are named as a differential mode $\ddot{x}^{dif}$ and a common mode $\ddot{x}^{com}$, respectively. If (6) is satisfied, a human operator feels accurate reaction force from an remote environment. $\hat{\boldsymbol{q}}$ is obtained as (7).

$$\hat{\boldsymbol{q}} = \boldsymbol{J(s)} \begin{bmatrix} \hat{\boldsymbol{x}} \\ \hat{\boldsymbol{f}}^{\boldsymbol{ext}} \end{bmatrix} = \begin{bmatrix} 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} \hat{\boldsymbol{x}} \\ \hat{\boldsymbol{f}}^{\boldsymbol{ext}} \end{bmatrix} \tag{7}$$

$\boldsymbol{E(s)}$ is obtained as (8).

$$\boldsymbol{E(s)} = \begin{bmatrix} e^{-T_1 s} & 0 \\ 0 & e^{-T_2 s} \end{bmatrix} \tag{8}$$

Where, $e^{-T_1 s}$ is an one-way delay between the master and the central controller. And $e^{-T_2 s}$ is an one-way delay between the slave and the central controller. T_1 is required to be equal to T_2 to estimate the modal vector $\boldsymbol{q} = [\ddot{x}^{dif} \ddot{x}^{com}]^T$. If master, slave and, the central controller are time synchronizing, it is easy to achieve $T_1 = T_2$. For example, time stamp is often utilized to maintain the constant communication delay between multiple PCs that are connected over a network.

$C_1(s)$ and $C_2(s)$ are obtained as (9) and (10).

$$\boldsymbol{C_2(s)} = \begin{bmatrix} C_p(s) & -C_f(s) \\ -C_p(s) & -C_f(s) \end{bmatrix} \tag{9}$$

$$C_2(s) = k_s + k_d s \tag{10}$$

Where, $C_p(s) := k_p + k_v s$ and $C_f := k_f$.

IV. Simulation

In this section, simulation results of the bilateral control are shown to confirm the validity of the proposed method.

A. Setup

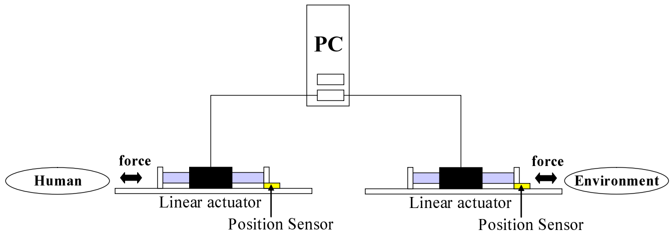


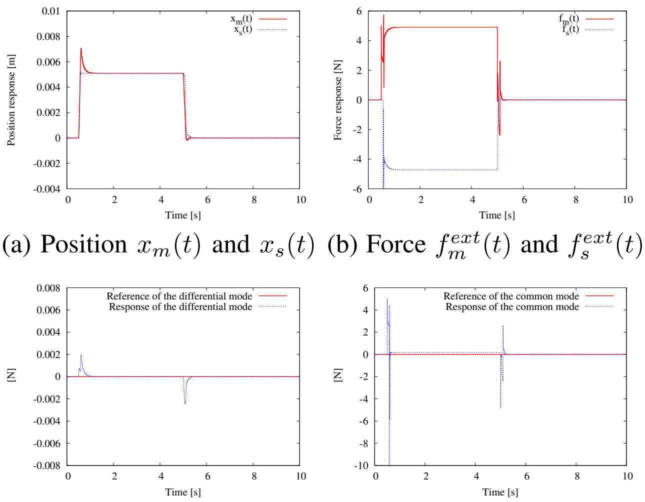
Fig. 6. An experimental system for the bilateral control

Fig. 6 is a structure of an experimental system for the bilateral control. This master/slave robot system is comprised of two linear motors and two position encoders. In this simulation, an operator applies the external force f_m^{ext} to the master robot. Then, the slave robot tracks the master one. When the slave robot contacts with the environment, external force f_s^{ext} is applied to the slave robot. If the bilateral control system satisfies (6), the operator feels accurate reaction force from the environment. In this simulation, the initial position of the master/slave robots are set to 0.0 [m]. The operator applies f_m^{ext} at the time 0.5 [s] in order to keep the position at 0.01 [m]. The remote environment is located at 0.005 [m]. Therefore, the slave robot contacts with the environment after the time 0.5 [s]. Then, the operator changes the position of the master robot to the initial position at the time 5.0 [s].

The proposed structure, that is shown in Fig. 4, is applied here. But two kinds of bilateral control systems are compared here. The first one is the conventional mode based position/force hybrid control system that is shown in Fig. 2. The second one is the proposed one that is shown in Fig. 5. In the case of the conventional method, CDOB is not utilized. So a delayed position information of the master robot and the slave robot is used directly to calculate an estimated modal vector. Parameters are listed in Table I. In the case of the conventional method, the cut-off frequency of a low pass filter for DOB (g_{dob}) is set to 20[s^{-1}]. One the other hand in the case of the proposed method, two kinds of DOB are utilized. The cut-off frequency of DOB that calculate $\hat{\boldsymbol{f}}^{\boldsymbol{ext}}$ (g_{dob}) at the plant side is set to 20[s^{-1}]. And, the cut-off frequency of

TABLE I
PARAMETERS IN SIMULATION

Mass	M	0.5[kg]
Nominal Mass	M_n	0.5[kg]
Thrust coefficient	K_t	30.0[N/A]
Nominal thrust coefficient	K_{tn}	30.0[N/A]
Position feedback gain	k_p	900[s^{-2}]
Velocity feedback gain	k_v	60[s^{-1}]
Force feedback gain	k_f	0.5[kg^{-1}]
Virtual spring gain	k_s	9[kg/s^2]
Virtual damper gain	k_d	6[kg/s]
Control period	t_c	1.0[ms]
Environmemt impedance	Z_e	50000+100s



(a) Position $x_m(t)$ and $x_s(t)$ (b) Force $f_m^{ext}(t)$ and $f_s^{ext}(t)$

(c) Differential mode $\ddot{x}^{dif}(t)$ (d) Common mode $\ddot{x}^{com}(t)$

Fig. 7. Simulation results of conventional method without delay (CASE 1)

DOB that calculate $\hat{\boldsymbol{x}}$ at the central controller (g_{cdob}) is set to 500[s^{-1}].

Two situations are assumed in this simulation. In CASE 1, T_1 and T_2 are set to 0[ms]. On the other hand, T_1 and T_2 are set to 30[ms] in CASE 2.

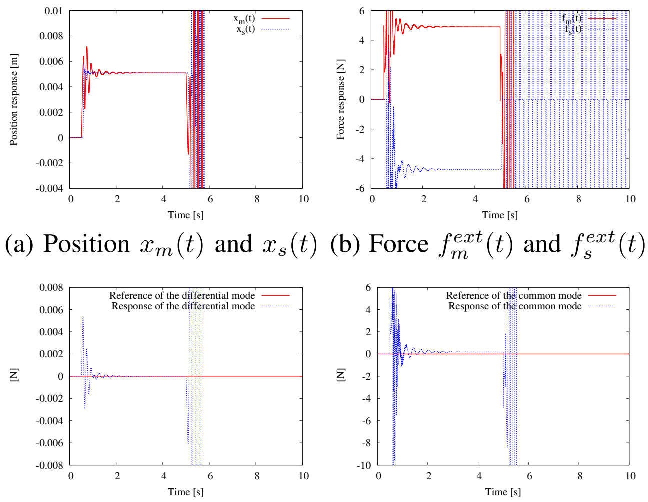
B. Results

Fig. 7 and Fig. 8 show the simulation results of the conventional method without a delay and with a delay,respectively. In Fig. 7, (6) is almost satisfied. So, a human operator feels accurate reaction force from an remote environment. But the system becomes unstable under the communication delay as shown in Fig. 8. This is the reason why the mode is hardly used for a hybrid control system with multiple plants that are connected through network with communication delay.

Fig. 9 and Fig. 10 show the simulation results of the proposed method without a delay and with a delay, respectively. The system does not become unstable under the communication delay because CDOB compensates the delay. But, the differential mode $\ddot{x}^{dif}$ has a large error. This error is caused by the estimation error of $\ddot{x}^{dif}$.

V. EXPERIMENT

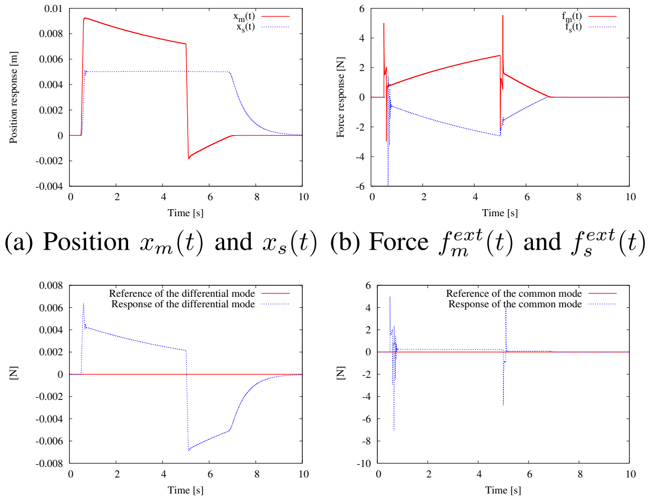
In this section, experimental results are shown to confirm the validity of the proposed method.



(a) Position $x_m(t)$ and $x_s(t)$ (b) Force $f_m^{ext}(t)$ and $f_s^{ext}(t)$

(c) Differential mode $\ddot{x}^{dif}(t)$ (d) Common mode $\ddot{x}^{com}(t)$

Fig. 8. Simulation results of conventional method with delay (CASE 2)



(a) Position $x_m(t)$ and $x_s(t)$ (b) Force $f_m^{ext}(t)$ and $f_s^{ext}(t)$

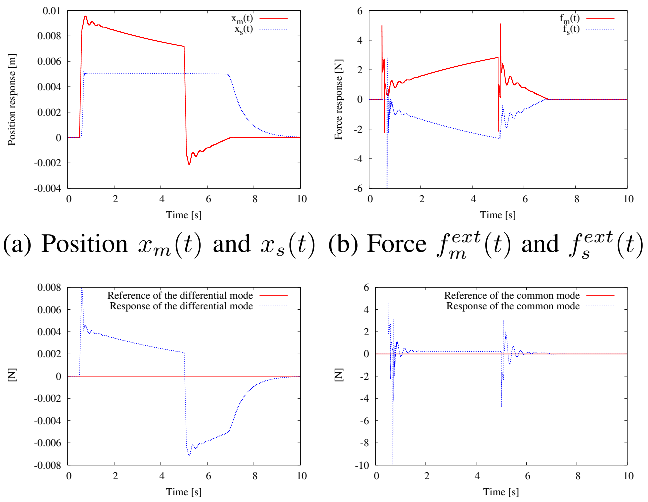
(c) Differential mode $\ddot{x}^{dif}(t)$ (d) Common mode $\ddot{x}^{com}(t)$

Fig. 9. Simulation results of proposed method without delay (CASE 1)

A. Setup

We performed experiments using the bilateral master/slave robots that is shown in Fig. 11. The structure of the experimental sytem is the same to Fig. 6. Position of the robot is measured by a position encoder. And an external force that is applied to the robot is estimated by not a force sensor but RFOB. In this experiment, slave robot contacted with hard environment (aluminum). The initial position of the master/slave robots are set to 0.0 [m]. The operator manipulates the master robot. The operation consists of two kinds of motion : a free motion and a contact motion. In the case of the contact motion, the operator feels a reaction force from the remote environment that is located around 0.03 [m].

The proposed structure, that is shown in Fig. 4, is applied here. But two kinds of bilateral control systems are compared here. The first one is the conventional mode based position/force hybrid control system that is shown in Fig. 2. And, the second one is the proposed one that is shown in



(a) Position $x_m(t)$ and $x_s(t)$ (b) Force $f_m^{ext}(t)$ and $f_s^{ext}(t)$

(c) Differential mode $\ddot{x}^{dif}(t)$ (d) Common mode $\ddot{x}^{com}(t)$

Fig. 10. Simulation results of proposed method with delay (CASE 2)

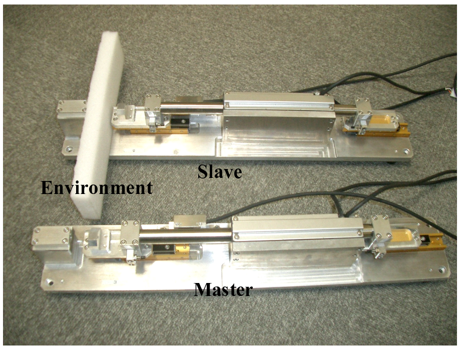


Fig. 11. The bilateral master/slave robots

Fig. 5. Parameters are listed in Table II. In the case of the conventional method, g_{dob} is set to 20[s^{-1}]. On the other hand in the case of the proposed method, g_{dob} and g_{cdob} are set to 20[s^{-1}] and 500[s^{-1}], respectively.

Two situations are assumed in this experiment. In CASE 1, T_1 and T_2 are set to 0[ms]. On the other hand, T_1 and T_2 are set to 20[ms] in CASE 2. These communication delays are virtually-inserted.

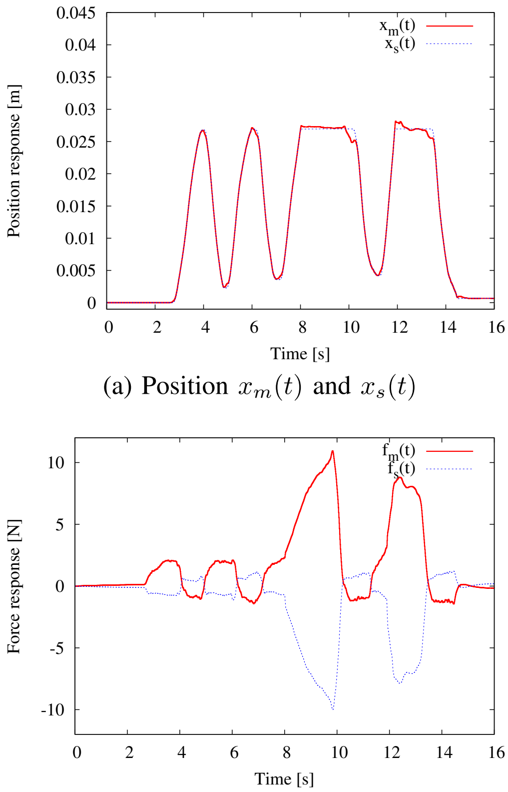
B. Results

Fig. 12 shows the experimental results of the conventional method without a communication delay. Because (6) is almost satisfied, a human operator feels accurate reaction force from an remote environment. But the system becomes unstable with a little communication delay.

Figs. 13–14 show the experimental results of the proposed method. In each case, a common mode $\ddot{x}^{com}$ is almost zero. So, an operator can feel a reaction force from a remote environment. But there is a position error between a master and a slave. This error makes it difficult to distinguish a soft environment and a hard environment.

TABLE II
PARAMETERS IN EXPERIMENT

Nominal Mass	M_n	0.5[kg]
Nominal thrust coefficient	K_{tn}	32.5[N/A]
Position feedback gain	k_p	900[s^{-2}]
Velocity feedback gain	k_v	60[s^{-1}]
Force feedback gain	k_f	0.5[kg^{-1}]
Virtual spring gain	k_s	9[kg/s^2]
Virtual damper gain	k_d	6[kg/s]
Control period	t_c	1.0[ms]



(a) Position $x_m(t)$ and $x_s(t)$

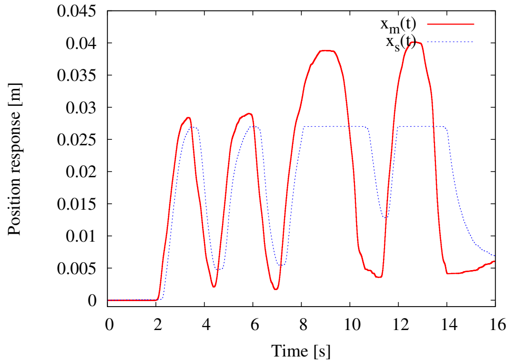
(b) Force $\hat{f}_m^{ext}(t)$ and $\hat{f}_s^{ext}(t)$

Fig. 12. Experimental results of conventional method without delay (CASE 1)

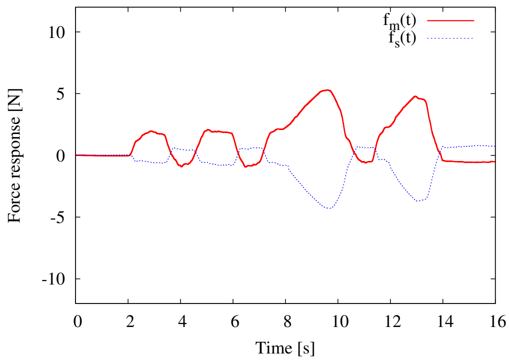
VI. Conclusion

A central controller for position/force hybrid control over network was proposed. In the proposed method, the central controller receives position and force information from each plant. Then, the central controller generates acceleration references for each plant by using a hybrid controller and a dead time compensator. As an application, bilateral control with communication delay was implemented. And some simulations and experiments verified the validity of the proposed method.

As a future works, a position error between each robot should be reduced. At present, CDOB can not estimate the differential mode accurately due to the disturbance that is applied to the plants. This is the reason why there is a large position error. Therefore, an improvement of CDOB is required.

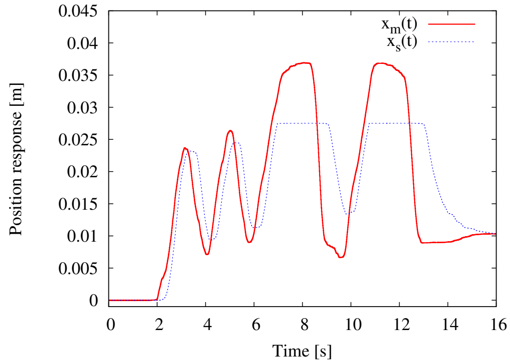


(a) Position $x_m(t)$ and $x_s(t)$

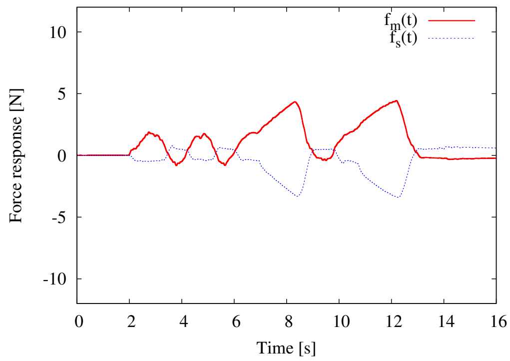


(b) Force $\hat{f}_m^{ext}(t)$ and $\hat{f}_s^{ext}(t)$

Fig. 13. Experimental results of proposed method without delay (CASE 1)



(a) Position $x_m(t)$ and $x_s(t)$



(b) Force $\hat{f}_m^{ext}(t)$ and $\hat{f}_s^{ext}(t)$

Fig. 14. Experimental results of proposed method with delay (CASE 2)

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