

Multilateral Control-Based Motion Copying System for Haptic Training

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Abstract—This paper proposes a new motion-loading method that utilizes a multilateral control-based scheme for the motion-copying system. The motion-copying system refers to human operator's motion, tracks and preserves it only for being able to reproduce the same result of the motion. Conventionally, only slave system was used for motion-loading phase. The method proposed in this paper offers a way to enable more than one slave side actuator at the phase. With the proposed system, the operator at loading phase can grab the master system which the manipulator was holding at the saving phase. The performance analyses of proposed system are made with the bode plots, and the experiments are held with two degrees-of-freedom actuators. The newly proposed haptic informational reproduction technique can be applied in many areas, especially as the training purposes.

I. INTRODUCTION

The human society is in an era of information and we need to preserve all the data we can. The acoustic and visual data preservation methods provided via cameras and microphones are becoming more and more common in today's world. However, those are insufficient since humans are capable of feeling not only sound and vision but also tactile sensation. In that sense, human race should also start preserving and reproducing the haptic information to increase the efficiency in learning, medical and industry fields. For that purpose the motion-copying system was researched, developed and worked on in [1-2]. Stability analyses of the system on different environments were done in [3].

Since haptic information is bilateral based on action-reaction law, it is hard to preserve and reproduce the human motion. The acquisition and communication between actuators should be done via bilateral control methods that utilize master and slave systems [4-7]. With the application of these methods, the preservation and reproduction are made possible. The concept of the motion-copying systems is based on the bilateral control methods: slave system is controlled with virtual master system in which the haptic data are stored. The systems is highly capable of reproducing and mimicking the position and force information of the human motions. Therefore, motion-copying system can be applied to many areas including industry, medical field and education.

Since the robots can reproduce the human motion using the method, with the help of experienced operators, they can highly influence the industry. At the hands of a skilled operator

a robot can now learn new methods that increase and speed up the production of merchandise. At the hands of a skilled surgeon a robot can become a great device of medical care and health. Human society is developing at a high pace and the reproduction of the haptic information can influence on this even more. It is easy to think of a classroom full of robots helping students learn with the recreation of the human motion. The usage of haptic information reproduction for educational purposes was actually worked on before [8].

The reproduction of human motion and utilization of robots for educational purposes are great ideas with even greater problems. The proposed method in [8] allows the reproduction of the calligraphy master's motion and it provides visual data to the students. However, it doesn't allow the students to actually touch the actuators. In the conventional motion-copying system, only slave side moves and it is difficult to tell the trainee how the trainer was manipulating the master system, which the skilled person was actually holding. In some applications of motion-copying system, there is a case that the master and slave devices are different: master device is used as a handle and slave device is an end-effector. In this case, the students cannot learn the motion since only slave actuator (end-effector) moves. Though the conventional motion-copying system is good for reproducing the saved motion, those are not customized for educational purposes: it does not consider that students grab the master system in loading phase. If there were two slave actuators while the motion is reproduced, one actuator would be able to do the calligraphy while the other actuator was held by the student that is learning calligraphy.

This paper proposes a method that utilizes a multilateral control-based scheme at the motion-loading phase which enables the usage of the second actuator that was used as the master side. Multilateral control is an expanded form of bilateral control, and it enables haptic communication among several actuators [9]. The motion-copying system using multilateral control is proposed in [10]. However, this method uses the multilateral control for both saving and loading for reproducing the cooperative motion. Different from this, proposed method uses bilateral control for saving and multilateral control for loading, in order to provide the trainee with the actuator which the operator was holding at saving phase. The contribution of this paper is a proposal of new framework of educational system on the basis of combination of multilateral control and

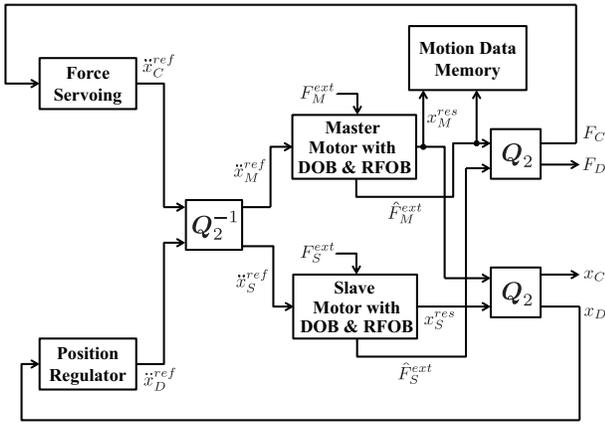


Fig. 1. Block diagram of the conventional method for motion saving system.

motion-saving based on bilateral control. Since the motion-copying system can be used beyond time and space, the student can repeat the motion until he perfects his calligraphy skills. In this paper, performance of the system is analyzed using bode plots, and experiments are shown to confirm the results of the analyses.

II. CONVENTIONAL MOTION-COPYING SYSTEM

The conventional motion-copying system is a combination of two steps that consist of motion-saving and motion-loading systems [8]. Motion-copying system copies the human motion via the master side, and reproduces it on the slave side whenever desired. The whole system is controlled via a bilateral control algorithm both on the motion-saving step and the motion-loading step.

The system uses two actuators on the motion-saving step: one actuator for the human operator to provide the position and force inputs of the motion and one actuator for the slave side to repeat what the master side is doing. While that is happening, all the information from the human operator is saved on the computer. Then, the motion-loading step starts and the information on the computer acts like a virtual master side to provide information to the slave side to reproduce the motion that was provided by the human operator beforehand.

Since the whole system is based on bilateral control, it uses force servoing and position regulation to provide acceleration and force references to the actuators. The disturbance and external forces on the actuators are calculated via disturbance and reaction force observers (DOB and RFOB) to provide the force servoing with the force information and to get rid of the disturbance on the actuator [11-12].

Next two sub-chapters explain the motion-saving and motion-loading systems in detail.

A. Motion Saving System

Fig. 1 shows a block diagram of the motion-saving system. In Fig. 1, x denotes position and F denotes force. Superscripts ref , res and ext denote reference, response and external value, respectively; while subscripts C , D , M and S denote common mode, differential mode, master and slave, respectively. Q_2 is

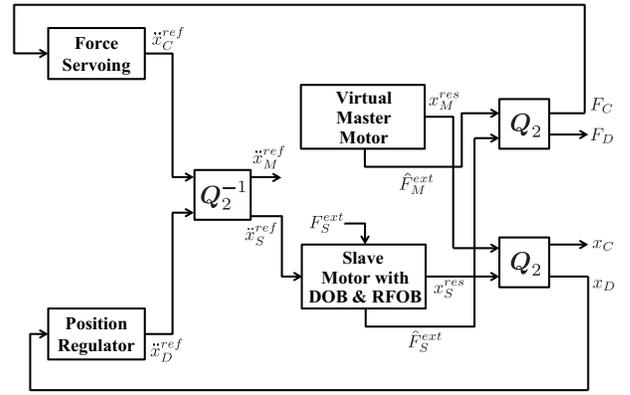


Fig. 2. Block diagram of the conventional method for motion loading system.

a second order quarry matrix used for calculating common and differential modes

$$Q_2 = \frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}. \quad (1)$$

It actually is a basic bilateral control system with a motion data memory to save the motion that is provided by the human operator. During the saving phase, the human operator is able to hold the master actuator and provide the position and force references. The human operator is able to touch the environment in the slave side through the bilateral controller. The human operator feels the environmental force that is acting on the slave side which is creating the external force on the system.

The systems are controlled to realize action-reaction law ($F_M^{ext} + F_S^{ext} = 0$) and position synchronization ($x_M^{res} - x_S^{res} = 0$). By doing so, all the information provided by the human operator is recreated on the slave side and thus, the slave side is acting the same way as the human side. For that to occur, the output of the system is converted into the common and differential mode variables (F_C and x_D) and passed through force servoing and position regulator as

$$\ddot{x}_C^{ref} = -C_f F_C \quad (2)$$

$$\ddot{x}_D^{ref} = -C_p x_D, \quad (3)$$

where C_f and C_p are force and position controller, respectively. Then, the information provided by those regulators are converted to the actuator space variables and used to create a control input that is able to make both the master and the slave sides to act the same.

During the saving phase, the output of the system is conserved at the motion data memory for further use at the loading phase. Basically, the motion-saving system saves the motion information that is provided by a human operator to be used at the motion-loading system beyond time and space.

B. Motion Loading System

Fig. 2 shows a block diagram of the conventional motion-loading system. The motion-loading system is the same with the motion-saving system except one thing: there is no human

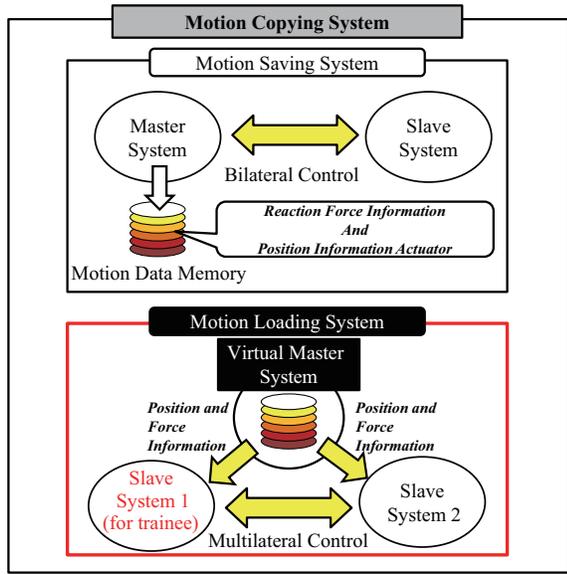


Fig. 3. Conceptual diagram of the newly proposed motion loading system.

operator to provide the reference. The reference is now provided by the virtual master motor which is actually the motion data memory which was used to save the information at the saving phase.

Using the motion information provided by the motion data memory, the motion-loading system follows the steps done at the motion-saving system: it provides force and position information to the regulators (force servoing and position regulator), and those regulators provide the control input to the system. The control input is then used by the slave actuator to provide the output which is the same with the one that was provided by the human operator at the saving phase.

The same bilateral algorithm is used at the motion-loading system except the regulators does not provide the control input to the master side. The master side is just the motion data memory that was saved beforehand. At the motion-loading phase, the system only cares about reproducing the motion that was provided by the human operator before. Thus, the motion-loading system only uses one actuator and the master side actuator that was once used to provide human operator's information to the system becomes useless during the motion-loading phase.

The reason behind utilizing bilateral control is that the motion provided by the human operator on the saving phase is haptic information. Therefore, it is subject to the law of action and reaction. One must utilize bilateral control algorithm to preserve both force and position responses at both phases and at both actuators. The actual master system has time-varying dynamic components; the disturbance observer compensates for these dynamic variations. Also the same structure for the master and slave sides is used to reflect the dynamics to the operator.

III. PROPOSED MOTION-LOADING SYSTEM

Fig. 3 shows the conceptual diagram of the proposed motion-loading system. In this newly proposed method, the

motion-saving phase stays the same as the conventional method; however the motion-loading phase utilizes a multi-lateral control algorithm to enable the usage of both actuators, utilizing the master side actuator to become useful during the motion-loading phase too. In the proposed method, the motion data memory again provides the position and force information; however now it provides the information to both actuators. Including the virtual master system, there are the communications between the three systems for multilateral control.

To enable this communication, number of the regulators is increased to three: one for force servoing and two for position regulation purposes. Therefore, the control inputs become three however one of them is not used because the master system is now virtual. Since both actuators are utilized, the master side that was once providing the human operator's reference to the motion data memory now becomes a slave side 1. Then, the original slave system that was acting on the environment becomes slave system 2. Again, the output of the actuators and the virtual master are converted into common and differential mode variables to be passed to the regulators in the modal space, and then they are converted into actuator space variables to create the multilateral control scheme.

Multilateral control is utilized in order to reproduce the force and position information for both of the slave actuators. Reaction force observers are utilized to calculate the external forces and disturbance observers are utilized to calculate the dynamic variations and to disable them.

Since the force and position information is provided to both systems, the whole system becomes a more complex one causing the analyses on performance to become difficult. In this paper, some assumptions are made for easy performance analyses. The analyses will be explained in detail at the next subchapter.

A. Performance Analyses

Fig. 4 shows the block diagram of the proposed motion-loading system used for the performance analyses. In Fig. 4, subscripts $D1$ and $D2$ denote primary and secondary differential modes and $S1$ and $S2$ denote primary and secondary slave motors. The performance analyses are made by calculating the transfer functions and checking the bode plots calculated via those transfer functions. For the easement of performance analyses, some assumptions are made here. It is assumed that there is no operational force, perfect acceleration control and perfect estimation at the reaction force observers are done [5]. Therefore,

$$\hat{F}_M^{ext} \simeq Z_s x_M^{res} \quad (4)$$

$$\ddot{x}^{ref} \simeq \ddot{x}^{res} \quad (5)$$

$$\hat{F}^{ext} \simeq F^{ext}, \quad (6)$$

where Z_s denotes the mechanical impedance of environment at the saving phase. In (4), the estimated master force \hat{F}_M^{ext} will include the term of $\frac{1}{C_f} \ddot{x}_M^{res}$, when operational force is considered.

Also as is seen from Fig. 4, there is no external force that is going into the first slave actuator and also it can be seen that there is no estimated external force from the first slave

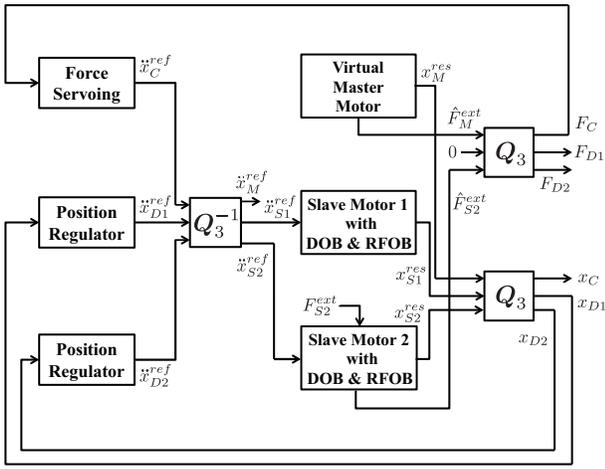


Fig. 4. Block diagram of the motion loading system for performance analysis.

actuator that is being converted into the modal space variable for the force servoing.

$$\hat{F}_{s1}^{ext} = 0 \quad (7)$$

The transfer functions for the performance analyses are calculated from the external force provided by the virtual master motor to the force output of the second slave motor. During those calculations, environmental impedance at saving phase is defined by spring-damper model as

$$Z_s = D_s s + K_s. \quad (8)$$

Then, environmental loading phase impedance is defined as

$$Z_l = D_l s + K_l. \quad (9)$$

The third order quarry matrix for multilateral control is shown as

$$Q_3 = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 0 & 1 & -1 \\ 2 & -1 & -1 \end{bmatrix}, \quad (10)$$

and the position regulation and force servoing are done by

$$C_p = K_p + K_d s \quad (11)$$

$$C_f = K_f. \quad (12)$$

In the equations above Z_l is mechanical impedances at loading phase, K_s and K_l are stiffness coefficients, D_s and D_l are damping coefficients. K_d is the differential gain for the position regulator, K_p is the proportional gain for the position regulator and K_f is the proportional gain for the force controller.

With all the above mentioned equations, the transfer function from \hat{F}_M^{ext} to \hat{F}_{S2}^{ext} is calculated as below

$$G_s = \frac{\hat{F}_{S2}^{ext}}{\hat{F}_M^{ext}} = \frac{a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0}{b_5 s^5 + b_4 s^4 + b_3 s^3 + b_2 s^2 + b_1 s + b_0}, \quad (13)$$

where the coefficients in the numerator are:

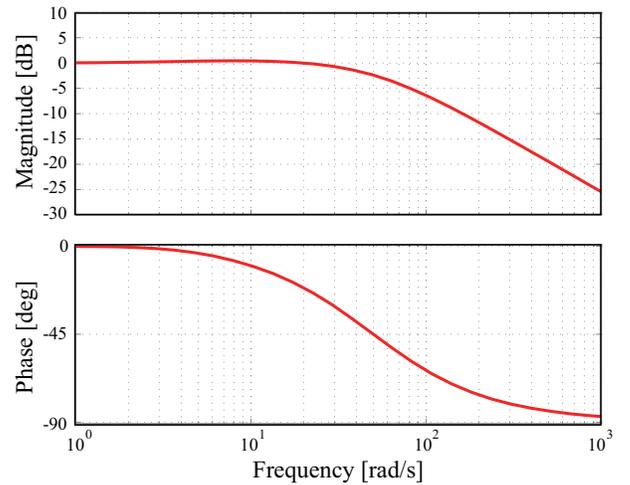


Fig. 5. Bode diagram for performance analysis.

$$a_4 = D_l \alpha \quad (14)$$

$$a_3 = K_l \alpha + D_l (K_{dl} \alpha + \beta) \quad (15)$$

$$a_2 = K_l (K_{dl} \alpha + \beta) + D_l (K_{pl} \alpha + K_{dl} \beta) \quad (16)$$

$$a_1 = K_l (K_{pl} \alpha + K_{dl} \beta) + D_l K_{pl} \beta \quad (17)$$

$$a_0 = K_l K_{pl} \beta, \quad (18)$$

and the coefficients in the denominator are:

$$b_5 = -3D_s \quad (19)$$

$$b_4 = -3K_s - D_s (3K_{dl} + \delta) \quad (20)$$

$$b_3 = -K_s (3K_{dl} + \delta) - D_s (3K_{pl} + K_{dl} \delta + \gamma) \quad (21)$$

$$b_2 = -K_s (3K_{pl} + K_{dl} \delta + \gamma) - D_s (K_{pl} \delta + K_{dl} \gamma) \quad (22)$$

$$b_1 = -K_s (K_{pl} \delta + K_{dl} \gamma) - D_s K_{pl} \gamma \quad (23)$$

$$b_0 = -K_s K_{pl} \gamma, \quad (24)$$

while the coefficients denoted as greek letters are:

$$\alpha = K_{d2} + D_s K_f \quad (25)$$

$$\beta = K_{p2} + K_s K_f \quad (26)$$

$$\delta = K_{d2} + D_l K_f \quad (27)$$

$$\gamma = K_{p2} + K_l K_f. \quad (28)$$

If the variable pairs such as K_{p1} and K_{p2} , K_{d1} and K_{d2} , D_s and D_l as well as K_s and K_l are set to be equal, then the bode plot calculation can be made. The performance calculation is made via (13). The result can be seen at Fig. 5. From here, the bandwidth of the system turns out to be around 10 Hz. The bandwidth is thought to be enough for tracking the human motion.

IV. EXPERIMENTS

In this section the experiments run with the 2-link manipulators are explained. The operation of the newly proposed motion-loading system is confirmed. Due to the experimental setup being a two degrees-of-freedom system, Jacobian matrix is introduced to the system. The following sub-chapters A, B and C will explain the experimental setup and the introduction of Jacobian matrix, results of the saving phase and results of the loading phase, respectively.

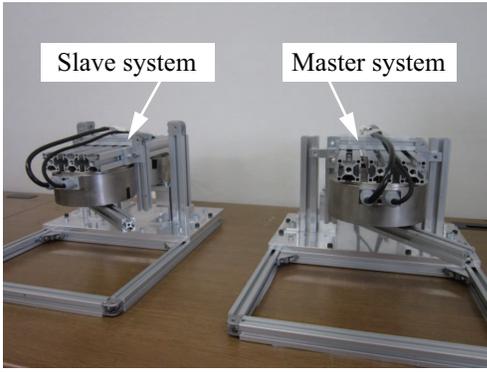


Fig. 6. Experimental setup for the motion copying system.

TABLE I. EXPERIMENTAL PARAMETERS

Parameter	Description	Value
T_s	Sampling time	0.1 ms
g_{d1}	Cut-off frequency of DOB for link 1	200.0 rad/s
g_{d2}	Cut-off frequency of DOB for link 2	200.0 rad/s
g_{r1}	Cut-off frequency of RFOB for link 1	200.0 rad/s
g_{r2}	Cut-off frequency of RFOB for link 2	200.0 rad/s
K_f	Force control gain	0.2
K_p	Proportional gain of position control	400.0
K_d	Differential gain of position control	40.0

A. Experimental Setup

Fig. 6 shows the experimental setup for the motion-copying system operation. During the experiment the actuator on the left side acted as the slave side for the motion-copying system. The human operator controlled the right hand side actuator via the metallic extension that can be seen on the picture. During the loading phase, both actuators acted as slaves. The motion-saving system preserves the human operator's reference and the motion-loading system reproduces it.

During the experiments, SGMCS-02BDC41 direct drive motors from Yasukawa Electrical Corporation were used at each link. Since the systems have two degrees-of-freedom, Jacobian matrix is introduced. Kinematics, Jacobian matrix and their applications are explained below. Position kinematics are

$$\mathbf{x} = \begin{bmatrix} l_1 \cos \theta_1 + l_2 \cos(\theta_1 + \theta_2) \\ l_1 \sin \theta_1 + l_2 \sin(\theta_1 + \theta_2) \end{bmatrix}, \quad (29)$$

where l_1 , l_2 , θ_1 and θ_2 denote the length and angle of link 1 and 2, respectively. Moreover, the vector \mathbf{x} is expressed as $\mathbf{x} = [x \ y]^T$ where y denotes displacement in vertical direction. The Jacobian matrix can be calculated via

$$\dot{\mathbf{x}} = \mathbf{J}_{aco} \dot{\boldsymbol{\theta}}, \quad (30)$$

provided

$$\mathbf{J}_{aco} = \frac{1}{l_1 l_2 \sin \theta_2} \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix}, \quad (31)$$

where

$$\boldsymbol{\theta} = [\theta_1 \ \theta_2]^T \quad (32)$$

$$J_{11} = -l_1 \sin \theta_1 - l_2 \sin(\theta_1 + \theta_2) \quad (33)$$

$$J_{12} = -l_2 \sin(\theta_1 + \theta_2) \quad (34)$$

$$J_{21} = l_1 \cos \theta_1 + l_2 \cos(\theta_1 + \theta_2) \quad (35)$$

$$J_{22} = l_2 \cos(\theta_1 + \theta_2). \quad (36)$$

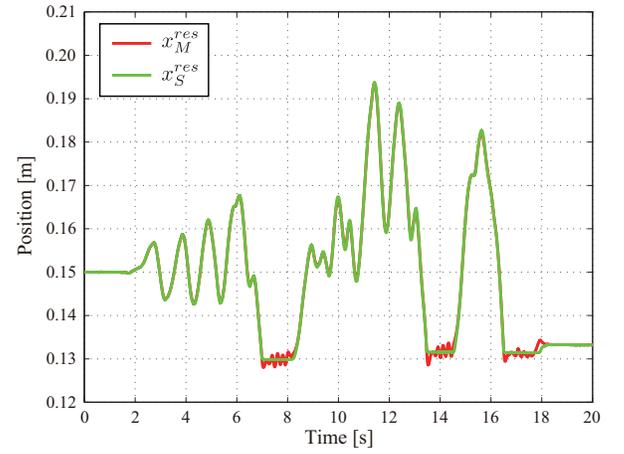


Fig. 7. Experimental results of motion saving system (position responses).

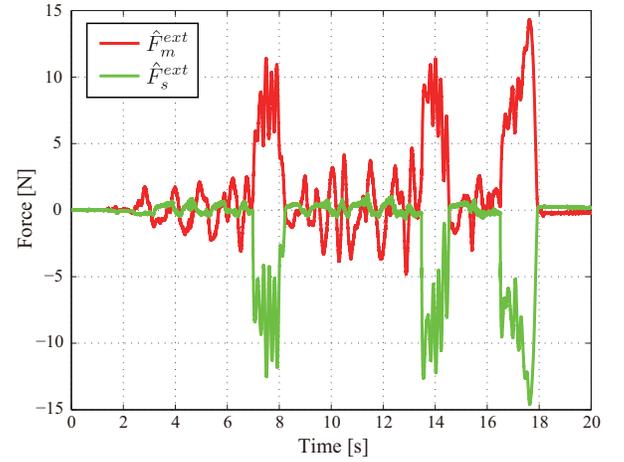


Fig. 8. Experimental results of motion saving system (force responses).

The Jacobian matrix is used for calculating the force in workspace and acceleration reference in joint space [13].

$$\hat{\mathbf{F}}^{ext} = \mathbf{J}_{aco}^{-T} \hat{\boldsymbol{\tau}}^{ext} \quad (37)$$

$$\ddot{\boldsymbol{\theta}}^{ref} = \mathbf{J}_{aco}^{-1} \ddot{\mathbf{x}}^{ref}, \quad (38)$$

where $\hat{\boldsymbol{\tau}}^{ext} = [\hat{\tau}_1^{ext} \ \hat{\tau}_2^{ext}]^T$ denotes estimated external torque in links 1 and 2. It can be seen from (31) that there are some singularity points. The singularities should be accounted since those cause the instability on the system.

The variables in Table I were used during the experiments. In Table I, T_s denotes sampling time, g marked with the superscripts ($d1$, $d2$, $r1$ and $r2$) denotes the gain of the low-pass filters used in the disturbance and reaction force observers.

B. Experimental Results of Saving Phase

Figs. 7 and 8 show the results of the position and force control of the motion-saving system. Due to the limitations of space, only results in x direction are shown (similar results are obtained in the control in y direction). As it can be seen, the position and force references are tracked by the slave actuator, and bilateral control is conducted. In the contact with environments, the operator repeated pushing motions rapidly,

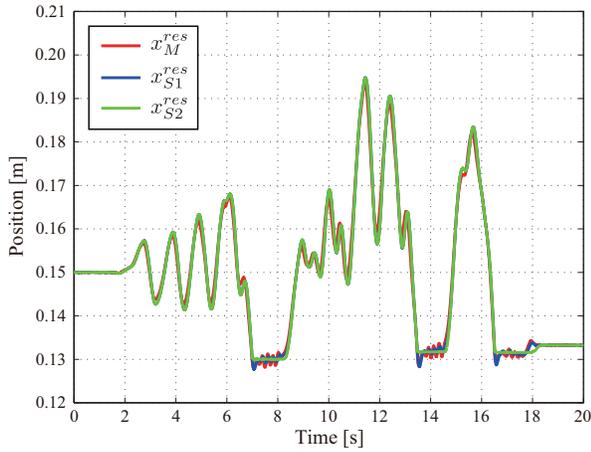


Fig. 9. Experimental results of motion loading system (position responses).

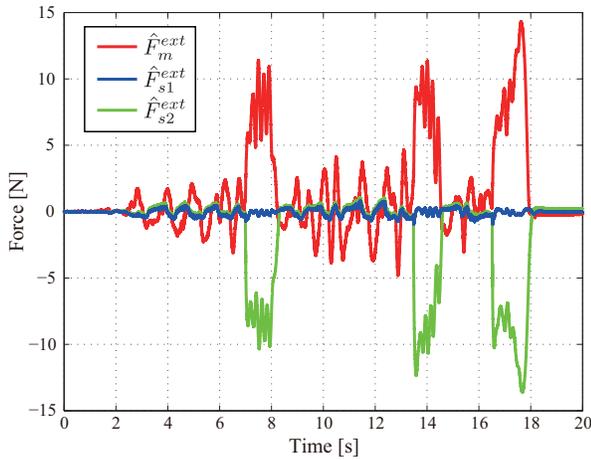


Fig. 10. Experimental results of motion loading system (force responses).

and those motions are well reproduced. In this phase, the responses of position and force are saved in motion data memory.

C. Experimental Results of Loading Phase

Figs. 9 and 10 show the results of the position and force control of the newly proposed motion-loading system. In this phase, same environment is placed in the slave 2 side, then no force is applied for slave 1 side based on the assumption of (7). It can be seen that the position and force references are tracked by both slave actuators and the validation of the derived transfer function is confirmed via experimentation. The small force responses of free motion in master system are operational force in saving phase, therefore those are not basically tracked by slave systems.

The objective of this paper is to drive another slave actuator so that the students can hold the master device in loading-phase, and it is assumed in this time that the student does not apply the force on the slave system 1. However, since the proposed system can detect the forces from environment and students separately, it is thought to be possible to adjust the control system to deal with the force from students. The

analyses and controller design with the consideration on the force will be focused as the future works of this study.

V. CONCLUSION

In this paper the reproduction of the motion provided by the human operator on multiple slaves is examined and it turned out to be validated. The performance of the system is theoretically confirmed by using the transfer functions and the bode plots. The system preserves the human operator's reference and reproduces it on both of the slave actuators.

The motion copying system can reproduce the human motion stored by an expert of some areas and the reproduction of human motion can be used for teaching purposes or surgical processes. By combining the saving-system based on bilateral control with the multilateral control-based loading system, the trainee can contact with the master system which the trainer was holding at the saving phase. In that sense, the newly proposed motion-loading system will be useful especially for educational purposes.

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