Bilateral Control of Master-Slave Manipulators for Ideal Kinesthetic Coupling—Formulation and Experiment

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Abstract— **In this paper, the analysis and design of master-slave teleoperation systems are discussed. The goal of this paper is to build a superior master-slave system that can provide good maneuverability. We first analyze a one degree-of-freedom system including operator and object dynamics. Second, some ideal responses of master-slave systems are defined and a quantitative index of maneuverability is given, based on the concept of ideal responses. Third, we propose new control schemes of master-slave manipulators that provide the ideal kinesthetic coupling such that the operator can maneuver the system as though he/she were directly manipulating the remote object himself/herself. The proposed control scheme requires accurate dynamic models of the master and slave arms, but neither parameters of the remote object nor the operator dynamics is necessary. Last, the proposed control scheme is introduced to a prototype master-slave system and the experimental results show the validity of the proposed scheme.**

I. Introduction

MASTER-SLAVE SYSTEMS have been applied to many areas since the 1960's when the first master-slave manipulator was developed [1], [2]. However, there has been little improvement in the control schemes of master-slave manipulators. The maneuverability of the current master-slave systems seems still far from satisfactory. Very recently, however, new control schemes aimed at high maneuverability have been proposed [3]–[6].

Certainly, the maneuverability of master-slave systems depends upon the quality of the mechanical design of manipulators. But the quality of control schemes also affects the maneuverability of the system. The goal of this paper is to build a superior master-slave system that can provide good maneuverability. There have been few serious discussions about how to evaluate the maneuverability of the system quantitatively. One of the problems is that since the "maneuverability" of the system is an intuitive property for human operators, it would be difficult to evaluate such an intuitive property quantitatively. Raju [7], [9] evaluated the maneuverability of master-slave systems experimentally. He pointed out that there are various aspects for evaluating the performance of the system. Another problem is that theoretical analysis of master-slave system is complex because both the operator dynamics and the object dynamics should be taken into account. Hannaford [11] also pointed out the importance to consider the whole system including not only the arm dynamics but also the object and operator dynamics for system stability analysis.

To evaluate the system performance or to design new control schemes, it would be meaningful to specify an ideal response of master-slave systems. Dudragne *et al.* [3] mentioned that the system should respond just like a virtual rod with infinitely small mass and infinitely large stiffness connected between the operator and remote site. They then specified an ideal state as the case when the hybrid matrix, which was originally defined in circuit theory, has a special value. This point was also shown by Hannaford [12]. But they did not exactly discuss to what extent the actual responses can reach the ideal one. Tachi *et al.* [13] proposed the impedance type control scheme in which an appropriate impedance model is introduced into each arm as a target model, and they mentioned that the smaller the impedance model is set, the closer the system response reaches to the ideal one. Kazerooni [14] proposed a concept of "telefunctioning," i.e., an extension of telepresence introducing appropriate functions between the master and slave sides. The authors also discussed the way to evaluate maneuverability of the system and proposed new bilateral control schemes that can realize the ideal kinesthetic coupling [15]–[18].

This paper consists of two parts. In the first part, Sections II through V, we propose a way to evaluate the maneuverability of master-slave systems quantitatively. We define three ideal responses of master-slave systems and give a quantitative performance index of maneuverability, which examines how close the actual responses are to the ideal one. In the second part, Sections VI and VII, we propose a new control scheme that provides the ideal kinesthetic coupling. The proposed scheme is a sort of dynamic control approach and it requires accurate dynamic models of the master and slave arms. However, parameters of the operator dynamics and remote object are not necessary. We show experimental results obtained by a prototype master-slave system.

II. Modeling of One DOF System

A. Modeling of Arms, Object, and Operator

Most master-slave systems consist of arms with multiple DOF. However, a one DOF system is considered in order to make the problem simple.

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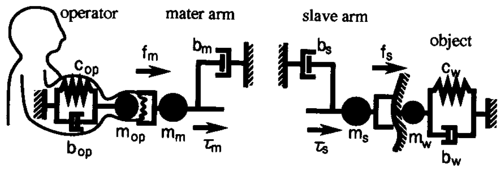

Fig. 1. Master and slave arms, operator and object.

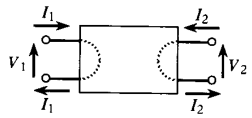

Fig. 2. Two-terminal-pair network.

The dynamics of master arm and slave arm is given by the following equations:

$$\tau_m + f_m = m_m \ddot{x}_m + b_m \dot{x}_m \quad (1)$$

$$\tau_s - f_s = m_s \ddot{x}_s + b_s \dot{x}_s \quad (2)$$

where x_m and x_s denote the displacements of the master and slave arms. And m_m and b_m represent mass and viscous coefficient of the master arm respectively, whereas m_s and b_s are those of the slave arm. In addition, f_m denotes the force that the operator applies to the master arm, and f_s denotes the force that the slave arm applies to the object. Actuator driving forces of master and slave arms are represented by τ_m and τ_s, respectively.

The dynamics of the object interacting with the slave arm is modeled by the following linear system:

$$f_s = m_w \ddot{x}_s + b_w \dot{x}_s + c_w x_s \quad (3)$$

where m_w, b_w, and c_w denote mass, viscous coefficient, and stiffness of the object, respectively. As the displacement of the object is represented by x_s in (3), we assume that the slave arm is rigidly contacting with the object or firmly grasping the object, in such a way that it may not depart from the object.

It is also assumed that the dynamics of the operator can be approximately represented as a simple spring-damper-mass system:

$$\tau_{op} - f_m = m_{op} \ddot{x}_m + b_{op} \dot{x}_m + c_{op} x_m \quad (4)$$

where m_{op}, b_{op} and c_{op} denote mass, viscous coefficient, and stiffness of the operator respectively, whereas τ_{op} means force generated by the operator's muscles. Similarly to (3), the displacement of the operator is represented by x_m in (4) because we assume that the operator is firmly grasping the master arm and he/she never release the master arm during the operation. It should be noted that the parameters of the operator dynamics may change during the operation. For example, Akazawa *et al.* [19] reported that b_{op} and c_{op} are proportional to the sum of the forces exerted by flexor and extensor muscles. Therefore these parameters are not constant. Fig. 1 shows the model of one DOF system.

B. Generalized Control Schemes of Master and Slave Arms

Let the following control schemes be considered as a general expression of the actuator inputs:

$$\tau_m = \left[K_{mpm} + K'_{mpm}\frac{d}{dt} + K''_{mpm}\frac{d^2}{dt^2} \quad K_{mfm} \right] \begin{bmatrix} x_m \\ f_m \end{bmatrix} - \left[K_{mps} + K'_{mps}\frac{d}{dt} + K''_{mps}\frac{d^2}{dt^2} \quad K_{mfs} \right] \begin{bmatrix} x_s \\ f_s \end{bmatrix} \quad (5)$$

$$\tau_s = \left[K_{spm} + K'_{spm}\frac{d}{dt} + K''_{spm}\frac{d^2}{dt^2} \quad K_{sfm} \right] \begin{bmatrix} x_m \\ f_m \end{bmatrix} - \left[K_{sps} + K'_{sps}\frac{d}{dt} + K''_{sps}\frac{d^2}{dt^2} \quad K_{sfs} \right] \begin{bmatrix} x_s \\ f_s \end{bmatrix} \quad (6)$$

where $K_{mpm}, K'_{mpm}, K''_{mpm}$ and K_{mfm} are feedback gains of the master arm position, velocity, acceleration and force, whereas $K_{mps}, K'_{mps}, K''_{mps}$ and K_{mfs} are gains of the slave arm position, velocity, acceleration, and force, respectively. These eight gains specify the input τ_m. Similarly, $K_{spm}, K'_{spm}, K''_{spm}, K_{sfm}, K_{sps}, K'_{sps}, K''_{sps}$, and K_{sfs} specify the input τ_s. Equations (5) and (6) are extensions of the formulation by Fukuda *et al.* [20]. Their original formulation does not contain velocity and acceleration terms. The conventional control schemes such as symmetric position servo type, force reflection type, and force-reflecting servo type can be represented as a special case of (5) and (6) with appropriate gains.

In (5) and (6), we assume an ideal situation where all the information (position, velocity, acceleration, and force) is available and time delay due to the data transmission between the master and slave sites is negligible. We also assume that the scales of position and force are identical between the master and slave sites. Practically speaking, however, we may face the situations where the scales are different between the operator and the remote object. It is possible to deal with such situations by introducing the scaling coefficients of position and force in (5) and (6). In this paper, however, we will consider the case when both scales are unity to simplify the discussion.

C. Representation of the Master-Slave System by Two-Terminal-Pair Network

Two-terminal-pair network is usually used in the analysis of electrical circuits. Impedance matrix $\boldsymbol{Z}$ is defined from the relations between current and voltage of a two-terminal-pair network shown in Fig. 2.

$$V_1 = z_{11} I_1 + z_{12} I_2 \quad (7)$$

$$V_2 = z_{21} I_1 + z_{22} I_2 \quad (8)$$

$$\boldsymbol{Z} = \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} \quad (9)$$

where I_1 and I_2 denote current at each terminal pair, and V_1 and V_2 denote voltage at each terminal pair.

Let us consider a two-terminal-pair network which is connected to a power source and a load at each terminal pair as shown in Fig. 3. Regarding the power source as an operator, the load as an object and the two-terminal-pair network as a master-slave system, the whole system can be replaced by the electric circuit in Fig. 3. The correspondence between the modeling in the previous section and the circuit representation in Fig. 3 is given as

velocity of the master arm $\dot{x}_m$	$\longleftrightarrow$	current I_m
velocity of the slave arm $\dot{x}_s$	$\longleftrightarrow$	current I_s
operator's force τ_{op}	$\longleftrightarrow$	voltage V_{op}
force at the master side f_m	$\longleftrightarrow$	voltage V_m
force at the slave side f_s	$\longleftrightarrow$	voltage V_s

Representation of the master-slave system by a two-terminal-pair network is not a new idea. However, Raju [7], [8] has shown the framework where the operator and object are considered as a power source and a load connected to the network. This circuit representation does not change the nature of the problem at all, but it enables us to formulate in compact forms.

Rewriting the actuator forces τ_m and τ_s into voltages T_m and T_s, respectively, in addition to the above correspondence, (1), (2), (5) and (6) are transformed from time domain into s-domain as follows:

$$T_m + V_m = (m_m s + b_m) I_m \triangleq Z_m I_m \tag{10}$$

$$T_s - V_s = (m_s s + b_s) I_s \triangleq Z_s I_s \tag{11}$$

$$\begin{aligned} T_m &= \left[K''_{mpm} s + K'_{mpm} + K_{mpm}\frac{1}{s} \quad K_{mfm}\right]\begin{bmatrix} I_m \\ V_m \end{bmatrix} \\ &\quad - \left[K''_{mps} s + K'_{mps} + K_{mps}\frac{1}{s} \quad K_{mfs}\right]\begin{bmatrix} I_s \\ V_s \end{bmatrix} \\ &\triangleq [P_m \quad Q_m]\begin{bmatrix} I_m \\ V_m \end{bmatrix} - [R_m \quad S_m]\begin{bmatrix} I_s \\ V_s \end{bmatrix} \end{aligned} \tag{12}$$

$$\begin{aligned} T_s &= \left[K''_{spm} s + K'_{spm} + K_{spm}\frac{1}{s} \quad K_{sfm}\right]\begin{bmatrix} I_m \\ V_m \end{bmatrix} \\ &\quad - \left[K''_{sps} s + K'_{sps} + K_{sps}\frac{1}{s} \quad K_{sfs}\right]\begin{bmatrix} I_s \\ V_s \end{bmatrix} \\ &\triangleq [P_s \quad Q_s]\begin{bmatrix} I_m \\ V_m \end{bmatrix} - [R_s \quad S_s]\begin{bmatrix} I_s \\ V_s \end{bmatrix}. \end{aligned} \tag{13}$$

Eliminating T_m and T_s from (10), (11), (12) and (13), the following equation is obtained.

$$\begin{aligned} &\begin{bmatrix} Z_m - P_m & -R_m \\ -P_s & -(Z_s + R_s) \end{bmatrix}\begin{bmatrix} I_m \\ -I_s \end{bmatrix} \\ &\quad = \begin{bmatrix} 1 + Q_m & -S_m \\ Q_s & -(1 + S_s) \end{bmatrix}\begin{bmatrix} V_m \\ V_s \end{bmatrix} \end{aligned} \tag{14}$$

Noting that I_1, I_2, V_1, and V_2 in Fig. 2 correspond to $I_m, -I_s, V_m$, and V_s in Fig. 3 respectively, elements of the impedance matrix of the master-slave system are given by

$$z_{11} = \frac{(1 + S_s)(Z_m - P_m) + S_m P_s}{(1 + S_s)(1 + Q_m) - S_m Q_s} \triangleq \frac{N_{11}}{D_Z} \tag{15}$$

$$z_{12} = \frac{-(1 + S_s)R_m + S_m(Z_s + R_s)}{(1 + S_s)(1 + Q_m) - S_m Q_s} \triangleq \frac{N_{12}}{D_Z} \tag{16}$$

$$z_{21} = \frac{(1 + Q_m)P_s + Q_s(Z_m - P_m)}{(1 + S_s)(1 + Q_m) - S_m Q_s} \triangleq \frac{N_{21}}{D_Z} \tag{17}$$

$$z_{22} = \frac{(1 + Q_m)(Z_s + R_s) - Q_s R_m}{(1 + S_s)(1 + Q_m) - S_m Q_s} \triangleq \frac{N_{22}}{D_Z}. \tag{18}$$

The determinant $|\boldsymbol{Z}|$ is given by

$$|\boldsymbol{Z}| = \frac{(Z_m - P_m)(Z_s + R_s) + P_s R_m}{(1 + S_s)(1 + Q_m) - S_m Q_s} \triangleq \frac{D_Y}{D_Z}. \tag{19}$$

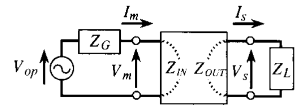

Fig. 3. Connection of power source and load to two-terminal-pair network.

The admittance matrix is obtained by inverting $\boldsymbol{Z}$.

$$\begin{aligned} \boldsymbol{Y} = \boldsymbol{Z}^{-1} &= \begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix} \\ &= \begin{bmatrix} \dfrac{N_{22}}{D_Y} & \dfrac{-N_{12}}{D_Y} \\ \dfrac{-N_{21}}{D_Y} & \dfrac{N_{11}}{D_Y} \end{bmatrix} \end{aligned} \tag{20}$$

Dynamics of the operator and object can also be represented in a form of impedance.

$$Z_L = m_w s + b_w + c_w \frac{1}{s} \tag{21}$$

$$Z_G = m_{op} s + b_{op} + c_{op} \frac{1}{s} \tag{22}$$

Equations (21) and (22) are obtained from the simple modeling of the operator and object in the previous subsection. Of course, one can suppose more appropriate impedance models for Z_L and Z_G if necessary.

III. Ideal Responses of Master-Slave Systems

In this section, before evaluating the performance of the system, we discuss what the ideal response of master-slave systems is. If the definition of the ideal response is valid, it would be possible to evaluate the performance of the system by examining how close the actual system response is to the ideal one.

A. Definition of Ideal Responses

Definition: The following three responses are defined as the ideal responses of master-slave systems.

Ideal Response I: The position responses x_m and x_s by the operator's input τ_{op} are identical, whatever the object dynamics is.

Ideal Response II: The force responses f_m and f_s by the operator's input τ_{op} are identical, whatever the object dynamics is.

Ideal Response III: Both the position response x_m and x_s, and the force responses f_m and f_s by the operator's input τ_{op} are identical respectively, whatever the object dynamics is.

Obviously, ideal response III means that both the position response and the force response coincide with the responses when the operator directly manipulates the remote object. Therefore, if ideal response III is realized, the operator can maneuver the system as if he/she were manipulating the remote object himself/herself. In this sense, ideal response III can be regarded as a final goal of master-slave systems: ideal kinesthetic coupling.

B. Conditions for Ideal Responses

The concept of the two-terminal-pair network is well used to design electric filters. The master-slave system can also be regarded as a sort of mechanical filter between the operator and the object. Here, we define some transmission coefficients in order to derive the conditions of the ideal responses.

First, we define the velocity transmission coefficient which specifies the transmission of velocity from the master side (I_m) to the slave side (I_s).

$$T_i \triangleq \frac{I_m}{I_s} \tag{23}$$

From (15) through (18) and the relationship of $V_s = Z_L I_s$, the velocity transmission coefficient is given by

$$T_i = \frac{z_{22} + Z_L}{z_{21}} = \frac{N_{22} + D_Z Z_L}{N_{21}}. \tag{24}$$

Since $T_i \equiv 1$ for any Z_L is necessary for realizing the ideal response I, the following conditions can be obtained.

1) Conditions for Ideal Response I:

$$\text{(A)} \quad D_Z = 0 \tag{25}$$

$$\text{(B)} \quad N_{21} = N_{22} \neq 0 \tag{26}$$

Next, we define the force transmission coefficient, T_v, which specifies the transmission of force from the master side (V_m) to the slave side (V_s).

$$T_v \triangleq \frac{V_m}{V_s} \tag{27}$$

Similarly, from (20) and the relationship of $V_s = Z_L I_s, T_v$ is given by

$$T_v = \frac{y_{22} + \frac{1}{Z_L}}{-y_{21}} = \frac{N_{11} Z_L + D_Y}{N_{21} Z_L}. \tag{28}$$

Since $T_v \equiv 1$ for any Z_L is necessary for realizing ideal response II, the following conditions are obtained.

2) Conditions for Ideal Response II:

$$\text{(C)} \quad D_Y = 0 \tag{29}$$

$$\text{(D)} \quad N_{21} = N_{11} \neq 0 \tag{30}$$

Note that T_v cannot be defined when $Z_L = 0$. It will be shown later that the conditions (C) and (D) are valid in this special case.[1]

When the both conditions for ideal responses I and II are satisfied, the system realizes ideal response III. Letting $x_m = x_s \triangleq x$ and $f_m = f_s \triangleq f$ in (3) and (4), it is obvious that x and f become the responses when the operator directly manipulates the object. In fact, the input impedance from the operator side is given by

$$Z_{IN} = z_{11} - \frac{z_{12} z_{21}}{z_{22} + Z_L} = \frac{D_Y + N_{11} Z_L}{N_{22} + D_Z Z_L}. \tag{31}$$

[1] See the footnote in Section IV.

And, substituting the conditions (A), (B), (C) and (D) into (31), we get

$$Z_{IN} \equiv Z_L \tag{32}$$

showing that the operator can feel the object impedance through the system.

3) Conditions for Ideal Response III: All of conditions (A), (B), (C) and (D).

Due to the conditions (A) and (C), impedance matrix and admittance matrix cannot be defined when the system is realizing the ideal response III. In fact, there is another matrix, called chain matrix, that specifies the property of two-terminal-pair network and can be defined even when the conditions (A) and (C) are satisfied. In Fig. 2, let the following relations be considered:

$$V_1 = k_{11} V_2 + k_{12}(-I_2) \tag{33}$$

$$I_1 = k_{21} V_2 + k_{22}(-I_2) \tag{34}$$

Chain matrix is defined by

$$\boldsymbol{K} \triangleq \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix}. \tag{35}$$

The chain matrix is used when the output of a two-terminal-pair network is connected to the input of another two-terminal-pair network. In the case of master-slave systems, the chain matrix can be represented by

$$\boldsymbol{K} = \frac{1}{z_{21}} \begin{bmatrix} z_{11} & |\boldsymbol{Z}| \\ 1 & z_{22} \end{bmatrix} = \begin{bmatrix} \frac{N_{11}}{N_{21}} & \frac{D_Y}{N_{21}} \\ \frac{D_Z}{N_{21}} & \frac{N_{22}}{N_{21}} \end{bmatrix}. \tag{36}$$

Elements of $\boldsymbol{K}$ correspond to the conditions (A), (B), (C) and (D). When all the conditions (A), (B), (C), and (D) are satisfied, we get

$$\boldsymbol{K} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}. \tag{37}$$

C. Design Guide of Control Schemes Realizing the Ideal Responses

In this subsection, we discuss the design policy for new control schemes that can realize the ideal responses. In (5) and (6), we have introduced acceleration terms to generalize the control schemes. Compared to position and velocity, however, acceleration is difficult to measure. So, it would be desirable if we could design a control scheme without acceleration terms.

However, it is impossible to satisfy the condition (C) when the acceleration signals are not used in (12) and (13), i.e., when $K''_{mpm} = K''_{mps} = K''_{spm} = K''_{sps} = 0$ in P_m, R_m, P_s, and R_s. Consequently, the following fact is obtained.

Proposition: In the framework of (5) and (6), any control scheme without acceleration terms cannot realize ideal response II nor III.

IV. Evaluation of Manueuverability

A high-performance master-slave system means that it can provide high maneuverability as well as stable operations. However, qualitative expressions such as "high maneuverability" and "stable operations" are not enough to evaluate the performance of the system. In this section, we propose a quantitative index of maneuverability based on the concept of the ideal responses introduced in the previous section.

A. Performance Index of Maneuverability

Let $G_{mp}(s), G_{sp}(s), G_{mf}(s)$, and $G_{sf}(s)$ be transfer functions of the master-slave system from the operator's force $\tau_{op}\,(V_{op})$ to the master side displacement $x_m\,(I_m/s)$, slave side displacement $x_s\,(I_s/s)$, master side force $f_m\,(V_m)$, and slave side force $f_s\,(V_s)$ respectively. These four transfer functions are given by

$$G_{mp}(s) = \frac{s[N_{22} + D_Z Z_L]}{s^2[D_Y + N_{11}Z_L + N_{22}Z_G + D_Z Z_L Z_G]} \quad (38)$$

$$G_{sp}(s) = \frac{s[N_{21}]}{s^2[D_Y + N_{11}Z_L + N_{22}Z_G + D_Z Z_L Z_G]} \quad (39)$$

$$G_{mf}(s) = \frac{s^2[D_Y + N_{11}Z_L]}{s^2[D_Y + N_{11}Z_L + N_{22}Z_G + D_Z Z_L Z_G]} \quad (40)$$

$$G_{sf}(s) = \frac{s^2[N_{21}Z_L]}{s^2[D_Y + N_{11}Z_L + N_{22}Z_G + D_Z Z_L Z_G]}. \quad (41)$$

By using these transfer functions, one can evaluate how well the actual system realizes the ideal responses.

1) Performance Index of Maneuverability: The following two indices are defined:

$$J_p = \int_0^{\omega_{\max}} |G_{mp}(j\omega) - G_{sp}(j\omega)| \left|\frac{1}{1+j\omega T}\right| d\omega \quad (42)$$

$$J_f = \int_0^{\omega_{\max}} |G_{mf}(j\omega) - G_{sf}(j\omega)| \left|\frac{1}{1+j\omega T}\right| d\omega \quad (43)$$

where $\omega_{\max}$ is the maximum frequency of the manipulation bandwidth of human operators, and $T\,(T\omega_{\max} > 1)$ is time constant of first-order-lag. One can evaluate the maneuverability of master-slave systems by checking how small the above indices are. When the system realizes the ideal response I, index J_p is zero. When the system realizes the ideal response II, index J_f is zero. Consequently, if both J_p and J_f are close to zero, the response of that system is close to the ideal response III. In (42) and (43), gain of first-order-lag is multiplied for the purpose of putting higher weight on the low frequency region than the high frequency region. Of course, any other weighting functions can be used.

A difficulty for evaluating the maneuverability with (42) and (43) is how to choose proper values of Z_L and Z_G which affect indices J_p and J_f. Therefore, it might be better to consider another indices which contain neither Z_L nor Z_G. On the other hand, it makes sense that the operator dynamics is taken into account for evaluating the maneuverability, because the maneuverability is measured just for the operator. So, we try to remove only Z_L from indices J_p and J_f.

Let us consider two special cases when $Z_L = 0$ and $Z_L = \infty$. The former case[2] corresponds to the situation where the slave arm is free. The latter corresponds to the case where the slave arm is constrained with a rigid environment. In these special cases, the subtractions of two transfer functions in (42) and (43) become as follows:

$[Z_L = 0]$

$$G_{mp}(s) - G_{sp}(s) = \frac{s[N_{22} - N_{21}]}{s^2[D_Y + N_{22}Z_G]} \quad (44)$$

$$G_{mf}(s) - G_{sf}(s) = \frac{s^2[D_Y]}{s^2[D_Y + N_{22}Z_G]} \quad (45)$$

$[Z_L = \infty]$

$$G_{mp}(s) - G_{sp}(s) = \frac{D_Z}{s[N_{11} + D_Z Z_G]} \quad (46)$$

$$G_{mf}(s) - G_{sf}(s) = \frac{s[N_{11} - N_{21}]}{s[N_{11} + D_Z Z_G]} \quad (47)$$

Making (44), (45), (46), and (47) be zero corresponds to the conditions (B), (C), (A), and (D) respectively. And one can get the performance indices which do not contain Z_L by substituting these equations (44) through (47) into (42) and (43).

B. Numerical Examples of Performance Evaluation

Let us evaluate the maneuverability of the conventional control schemes such as symmetric position servo type, force reflection type, and force-reflecting servo type by the proposed indices. Parameters of the master and slave arms are given by

$$m_m = m_s = 6.0\,[\mathrm{kg}], \quad b_m = b_s = 0.1\,[\mathrm{Ns/m}].$$

The following three kinds of object are considered.

[object 1]: $m_w = 0.5\,[\mathrm{kg}]$, $b_w = 0.1\,[\mathrm{Ns/m}]$, $c_w = 1.0\,[\mathrm{N/m}]$

[object 2]: $m_w = 3.0\,[\mathrm{kg}]$, $b_w = 1.0\,[\mathrm{Ns/m}]$, $c_w = 50.0\,[\mathrm{N/m}]$

[object 3]: $m_w = 1.0 \times 10^4\,[\mathrm{kg}]$, $b_w = 2.0 \times 10^4\,[\mathrm{Ns/m}]$, $c_w = 4.0 \times 10^4\,[\mathrm{N/m}]$

We supposed that object 1 is relatively soft, object 2 is relatively hard, and object 3 is a nearly rigid one. To simplify the problem, we set the parameters of the operator by the following constant values:

$$m_{op} = 2.0\,[\mathrm{kg}], \quad b_{op} = 2.0\,[\mathrm{Ns/m}], \quad c_{op} = 10.0\,[\mathrm{N/m}].$$

Control gains of each scheme were chosen as follows:

[2] In the case when $Z_L = 0$, substituting (C) and (D) into (40) and (41), $G_{mf}(s) = 0$ and $G_{sf} = 0$ are obtained. It means that $f_m = f_s = 0$ and the ideal response II is realized. Therefore the conditions (C) and (D) are valid even in this case.

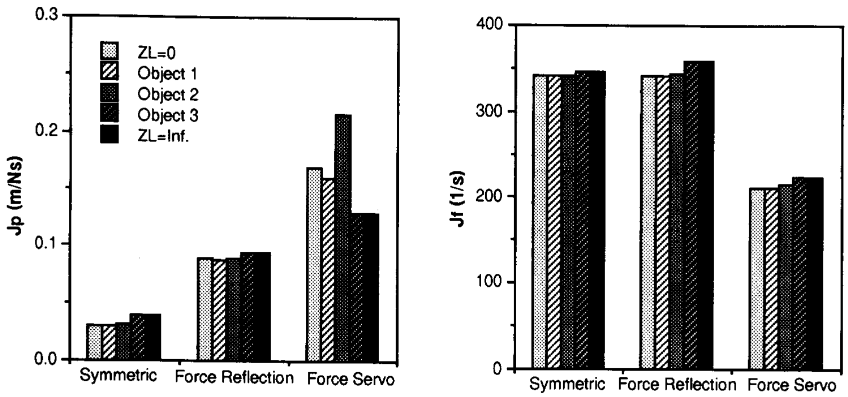

Fig. 4. Numerical example of maneuverability index.

1) Symmetric Position Servo Type:

$$K_{mpm} = K_{mps} = -400\,[\mathrm{N/m}], \quad K'_{mpm} = -50\,[\mathrm{Ns/m}]$$
$$K_{spm} = K_{sps} = 400\,[\mathrm{N/m}], \quad K'_{sps} = 50\,[\mathrm{Ns/m}]$$

2) Force Reflection Type:

$$K_{mfs} = 1.0, \quad K_{spm} = K_{sps} = 400\,[\mathrm{N/m}]$$
$$K'_{sps} = 50\,[\mathrm{Ns/m}]$$

3) Force-Reflecting Servo Type:

$$K_{mfm} = 2.5, K_{mfs} = 3.5$$
$$K_{sps} = K_{spm} - 400\,[\mathrm{N/m}], \quad K'_{sps} = 50\,[\mathrm{Ns/m}]$$

Actuator driving forces, τ_m and τ_s, are obtained by (5) and (6). Other gains that are not specified above are zero.

Fig. 4 shows the indices J_p and J_f defined by (42) and (43) in the cases when $Z_L = 0$ and ∞ in addition to the three objects. We set $\omega_{\max} = 100\,[\mathrm{Hz}]$ and $1/T = 50\,[\mathrm{Hz}]$. Symmetric position servo type shows small J_p but J_f is large. Force-reflecting servo types give larger J_p than symmetric position servo types, but J_f is smaller than the other two schemes.

Since this numerical result is an example with the particular gains, we cannot conclude which control scheme is the best. But the evaluation by the proposed indices seems reasonable. As shown in Fig. 4, indices J_p and J_f give different values according to the object parameters. If we could estimate the range of the object parameters in advance, we may be able to get indices J_p and J_f for the estimated object parameters. On the contrary, if we cannot estimate the object parameters, we can evaluate the system with J_p and J_f using $Z_L = 0$ and ∞. Of course, it is very important to use accurate parameters of the operator in order to obtain meaningful results. However, the parameters such as b_{op} and c_{op} may fluctuate according to the given task. For example, b_{op} and c_{op} may be small when $Z_L = 0$, whereas they may be large when $Z_L = \infty$. Estimation of appropriate parameters of the operator dynamics for a given task remains for future work.

Fig. 5. Ideal state of master-slave system.

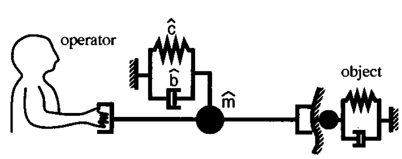

Fig. 6. Intervening impedance model.

V. Evaluation of Stability

A. Linear Systems Case

For precise analysis of stability, it is necessary to consider the whole system including the operator and object dynamics. Characteristic polynomial of four transfer functions in (38) through (41) is given by

$$H(s) = s^2[D_Y + N_{11}Z_L + N_{22}Z_G + D_Z Z_L Z_G]. \quad (48)$$

Of course, if all the roots of (48) are in the left halfplane of complex number plane, the system is stable. However, it is difficult to obtain general conditions of stability because Z_L and Z_G are not constant.

B. Passivity of the System

The characteristic equation approach is applicable only when the dynamics of the operator and object can be represented by linear systems like (3) and (4). Strictly speaking, however, the operator dynamics and some of the object dynamics may be nonlinear. In this subsection, we discuss the system stability based on the passivity of the system.

Raju [7], [8] showed that the positive definiteness of the impedance matrix is a sufficient condition of stability. However, this condition cannot be applied to the case when the

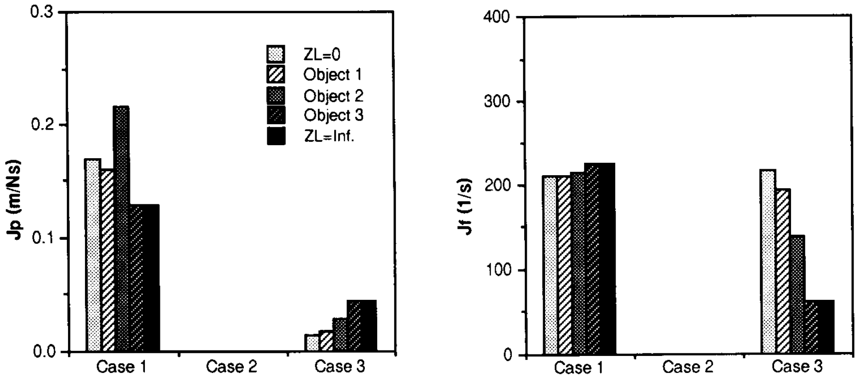

Fig. 7. Maneuverability indices of the proposed schemes.

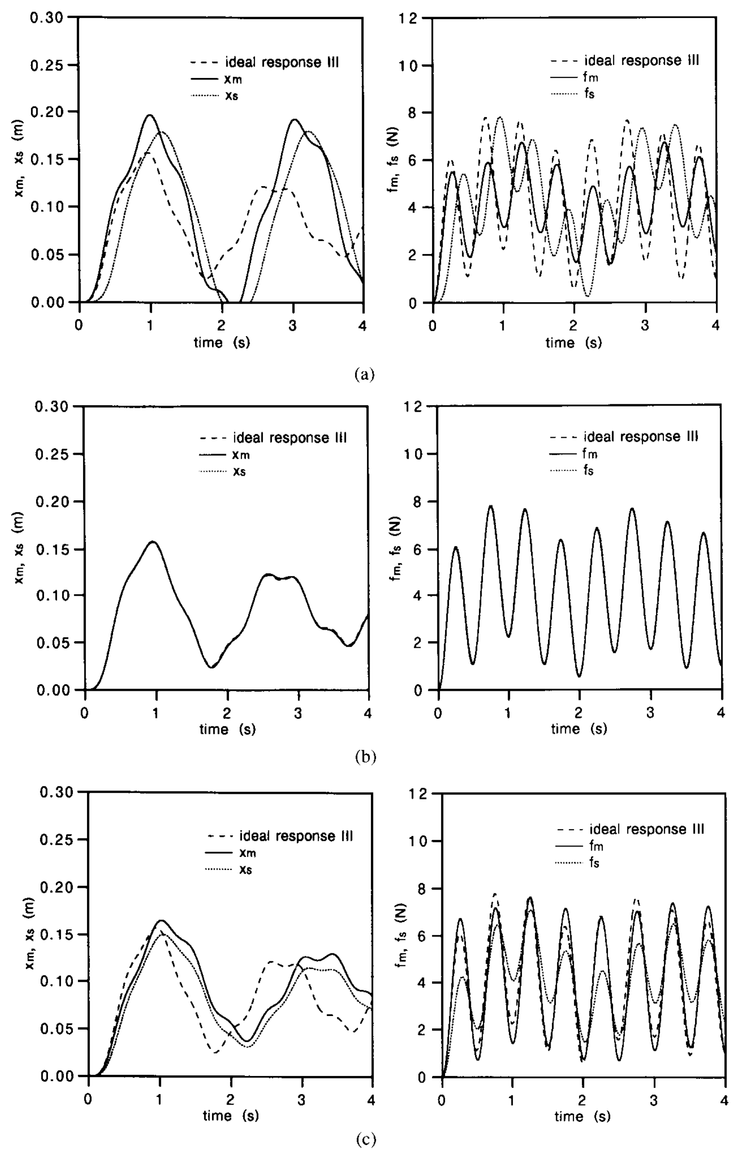

Fig. 8. Simulation results. (a) Case 1 (max $|\tau_m|$ = 18.78[N], max $|\tau_s|$ = 13.40[N]). (b) Case 2 (max $|\tau_m|$ = 13.28[N], max $|\tau_s|$ = 16.79[N]). (c) Case 3 (max $|\tau_m|$ = 11.19[N], max $|\tau_s|$ = 11.00[N]).

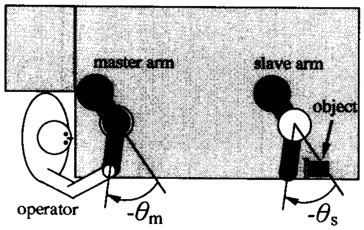

Fig. 9. One DOF experimental system.

condition (A) is satisfied. Colgate *et al.* [21] showed that the necessary and sufficient condition of stability for the system that may interact to any passive environment is that the system itself must be passive. Burnett [22] had already pointed out that the passivity is a sufficient condition for the system to remain stable for any passive load, and he showed that the symmetric position servo type satisfies this condition. Anderson *et al.* [23] also discussed the stability of the master-slave systems with time-delay by checking the passivity of the system.

Note that passivity itself is not an exact condition of stability in an input-output sense. For example, a lossless passive system such like mass-spring system may generate unbounded outputs by bounded inputs. Passivity of the system can be a sufficient condition of stability only when the system interacts passive environments. In the case of master-slave systems, if we could assume that the operator and the environment are passive systems, then the sufficient condition of stability is that the master-slave system itself must be passive. Strictly speaking, however, the operator is not passive because he/she has muscles as the power source. Colgate *et al.* [21] mentioned that even if the system has an active term, the system stability is guaranteed unless the active term is in some way state-dependent. Obviously, the operator is passive when $\tau_{op} = 0$. Therefore, we will give the following assumption about τ_{op}: "*The operators input τ_{op} is independent to the state of the master-slave system. In other words, the operator does not generate τ_{op} that will cause the system to be unstable.*" Dudragne *et al.* [3] gave a similar assumption in order to use the concept of passivity for stability distinction. The above assumption seems tricky in a sense, but it is necessary to ensure the system stability by the passivity.

Let us derive the conditions of passivity from the circuit representation. First, we define two vectors $\boldsymbol{V} \triangleq [V_m \quad V_s]^T$ and $\boldsymbol{I} \triangleq [I_m \; - I_s]^T$. The system is passive when the power P consumed in the system satisfies the following equation:

$$\begin{aligned} P &= \mathrm{Re}\,(V_m^* I_m - V_s^* I_s) \\ &= \left(\frac{\boldsymbol{V}+\boldsymbol{I}}{2}\right)^* \left(\frac{\boldsymbol{V}+\boldsymbol{I}}{2}\right) - \left(\frac{\boldsymbol{V}-\boldsymbol{I}}{2}\right)^* \left(\frac{\boldsymbol{V}-\boldsymbol{I}}{2}\right) \\ &= \boldsymbol{a}^*\boldsymbol{a} - \boldsymbol{b}^*\boldsymbol{b} \\ &= \boldsymbol{a}^*(\boldsymbol{E}_2 - \boldsymbol{S}^*\boldsymbol{S})\boldsymbol{a} \geq 0 \end{aligned} \tag{49}$$

where superscript * denotes conjugate transpose. The matrix $\boldsymbol{S}$ in (49) is called scattering matrix. Scattering matrix specifies the relation between the input wave to the system, $\boldsymbol{a} \triangleq (\boldsymbol{V} + \boldsymbol{I})/2$, and the output wave from the system, $\boldsymbol{b} \triangleq (\boldsymbol{V} - \boldsymbol{I})/2$.

$$\boldsymbol{b} = \boldsymbol{S}\boldsymbol{a}. \tag{50}$$

From (49), passive systems satisfy the following inequality:

$$||\boldsymbol{S}|| = \max_{\boldsymbol{x}} \frac{||\boldsymbol{S}\boldsymbol{x}||}{||\boldsymbol{x}||} = \max \lambda^{1/2}(\boldsymbol{S}^*\boldsymbol{S}) \leq 1. \tag{51}$$

In other words, the system is passive if the maximum singular value of $\boldsymbol{S}$ is less than or equal to 1 [23].

The scattering matrix $\boldsymbol{S}$ of the master-slave system is given by

$$\boldsymbol{S} = \frac{1}{D_Y + N_{11} + N_{22} + D_Z} \times \begin{bmatrix} D_Y + N_{11} - N_{22} - D_Z & 2N_{12} \\ 2N_{21} & D_Y - N_{11} + N_{22} - D_Z \end{bmatrix}. \tag{52}$$

If the maximum singular value of $\boldsymbol{S}$ in (52) is less than or equal to 1, the system stability is guaranteed for any passive objects under the assumption about τ_{op}.

VI. Design of Control Schemes Realizing the Ideal Responses

A. Control Scheme Realizing the Ideal Response III

In this section, we try to design control schemes that realize the ideal responses based on the results obtained in Section III. First, we design a control scheme which realizes the ideal response III.

Let the following basic form of control schemes be considered:

$$\tau_m = m_m u_m + b_m \dot{x}_m - k_{mf}\left(\frac{f_s - f_m}{2}\right) - \frac{f_m + f_s}{2} \tag{53}$$

$$\tau_s = m_s u_s + b_s \dot{x}_s - k_{sf}\left(\frac{f_s - f_m}{2}\right) + \frac{f_m + f_s}{2} \tag{54}$$

where k_{mf} and k_{sf} (≥ 0) are force gains, and u_m and u_s are new inputs. Equations (53) and (54) satisfy the condition (A) derived in Section III unless force signals are used in the new inputs u_m and u_s. We assume that physical parameters of each arm, such as m_m, m_s, b_m and b_s, are exactly known. Substituting (53) and (54) into (1) and (2) respectively, the following equations are obtained:

$$\ddot{x}_m = u_m - \frac{1}{m_m}(1 + k_{mf})\left(\frac{f_s - f_m}{2}\right) \tag{55}$$

$$\ddot{x}_s = u_s - \frac{1}{m_s}(1 + k_{sf})\left(\frac{f_s - f_m}{2}\right). \tag{56}$$

Adding both sides of (55) and (56), we obtain

$$\ddot{x}_m + \ddot{x}_s = u_m + u_s - \left(\frac{1 + k_{mf}}{m_m} + \frac{1 + k_{sf}}{m_s}\right) \cdot \left(\frac{f_s - f_m}{2}\right) \tag{57}$$

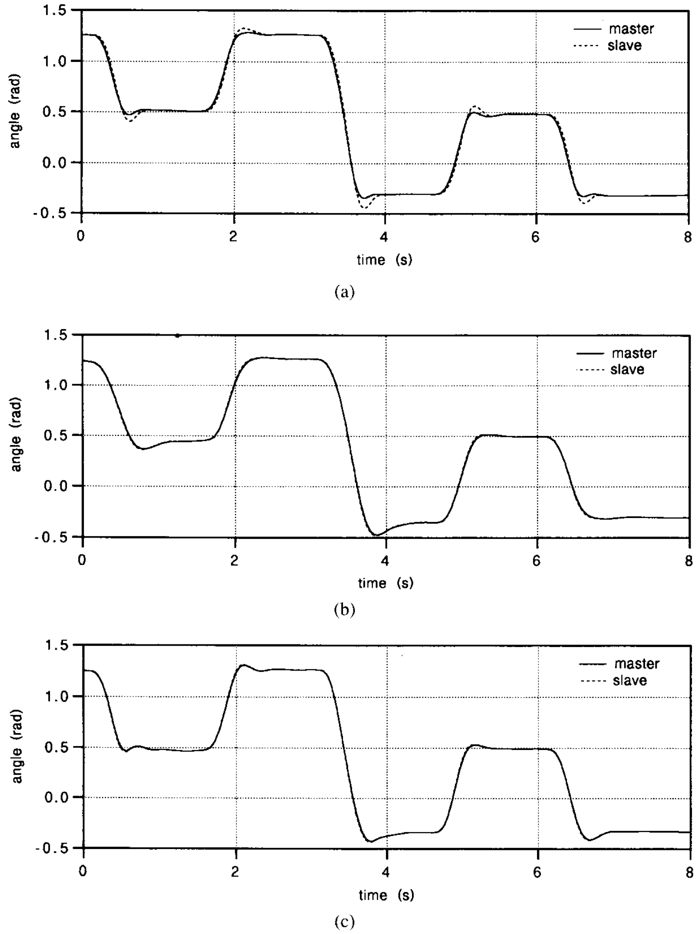

Fig. 10. Experimental results: position responses in Task 1. (a) Conventional force-reflecting servo type. (b) Proposed type with $\kappa = 0.0$. (c) Proposed type with $\kappa = 0.8$.

In (57), if

$$\ddot{x}_m + \ddot{x}_s = u_m + u_s \tag{58}$$

can be satisfied, we get

$$f_m - f_s = 0. \tag{59}$$

Equation (59) means that at least the ideal response II has been realized. Then, subtracting both sides of (56) from (55) and considering (59), we get

$$\ddot{e} = u_m - u_s \tag{60}$$

where $e \triangleq x_m - x_s$ denotes the position error between the two arms. Equation (60) shows that the behavior of $\ddot{e}$ can be specified by $u_m - u_s$. Here, we set $u_m - u_s$ as follows:

$$u_m - u_s = -k_1\dot{e} - k_2 e. \tag{61}$$

Then, we get

$$\ddot{e} + k_1\dot{e} + k_2 e = 0. \tag{62}$$

Equation (62) means that e converges asymptotically into zero with appropriate gains k_1 and k_2, and the ideal response III can be realized. From (58) and (61), u_m and u_s are obtained as follows:

$$u_m = \tfrac{1}{2}(\ddot{x}_m + \ddot{x}_s) - \tfrac{1}{2}k_1\dot{e} - \tfrac{1}{2}k_2 e \tag{63}$$

$$u_s = \tfrac{1}{2}(\ddot{x}_m + \ddot{x}_s) + \tfrac{1}{2}k_1\dot{e} + \tfrac{1}{2}k_2 e. \tag{64}$$

Finally, the control scheme is obtained as follows:

$$\begin{aligned}\tau_m &= m_m[\ddot{x}_{ms} + k_1(\dot{x}_{ms} - \dot{x}_m) + k_2(x_{ms} - x_m)] \\ &\quad + b_m\dot{x}_m - k_{mf}(f_{ms} - f_m) - f_{ms}\end{aligned} \tag{65}$$

$$\begin{aligned}\tau_s &= m_s[\ddot{x}_{ms} + k_1(\dot{x}_{ms} - \dot{x}_s) + k_2(x_{ms} - x_s)] \\ &\quad + b_s\dot{x}_s - k_{sf}(f_{ms} - f_s) - f_{ms}\end{aligned} \tag{66}$$

where $x_{ms} \triangleq (x_m + x_s)/2$ and $f_{ms} \triangleq (f_m + f_s)/2$. Equations (65) and (66) can be interpreted as a combined scheme of the computed torque method with the force control, where the computed torque method makes the arm follow the desired trajectory x_{ms} and the force control part regulates both f_m and f_s at f_{ms}. Force gains k_{mf} and k_{fs} in (65) and (66) do not give any effects because (59) is realized.

It should be noted that we assumed that arm parameters m_m, m_s, b_m and b_s are exactly known, whereas no parameters

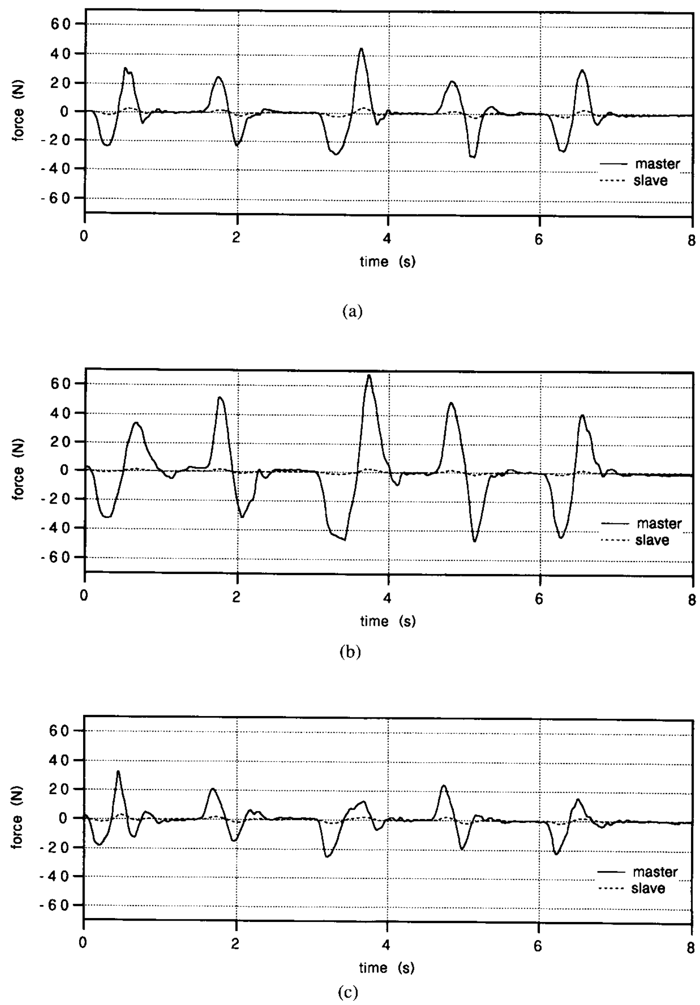

Fig. 11. Experimental results: force responses in Task 1. (a) Conventional force-reflecting servo type. (b) Proposed type with $\kappa = 0.0$. (c) Proposed type with $\kappa = 0.8$.

of the operator dynamics and the object are required for the proposed scheme. In other words, once we identified the parameters of master and slave arms, we can build the controller without knowing the operator and object dynamics.

However, identified parameters of the master and slave arms may contain some errors, and not only these parameter errors but also noises of the acceleration and force signals and the computation delays may cause the system to be unstable. Several researchers have discussed the robustness of the computed torque method for trajectory control of manipulators with respect to the uncertainty of the parameters. By choosing appropriate feedback gains, the controller provides an arbitrary small tracking error capability for the particular class of the desired trajectories [24]. In our case, the parameter uncertainty or time delay may spoil the realization of (58). Consideration of robustness of the controller against these factors remains for future work.

From (65) and (66), we get

$$
\begin{aligned}
P_m &= \frac{m_m}{2}(s - k_1 - k_2/s) + b_m, & Q_m &= \frac{1}{2}(k_{mf} - 1)\\
R_m &= -\frac{m_m}{2}(s + k_1 + k_2/s), & S_m &= \frac{1}{2}(k_{mf} + 1)\\
P_s &= \frac{m_s}{2}(s + k_1 + k_2/s), & Q_s &= \frac{1}{2}(k_{sf} + 1)\\
R_s &= \frac{m_s}{2}(-s + k_1 + k_2/s) - b_s, & S_s &= \frac{1}{2}(k_{sf} - 1)
\end{aligned}
$$

and we can show that the proposed scheme satisfies the conditions of the ideal response III.

B. Control Schemes Realizing the Ideal Responses I and II

In the previous subsection, we have proposed a new control scheme which realizes the ideal response III. The proposed scheme completely cancels the dynamics of both the master and slave arms which actually exists between the operator and

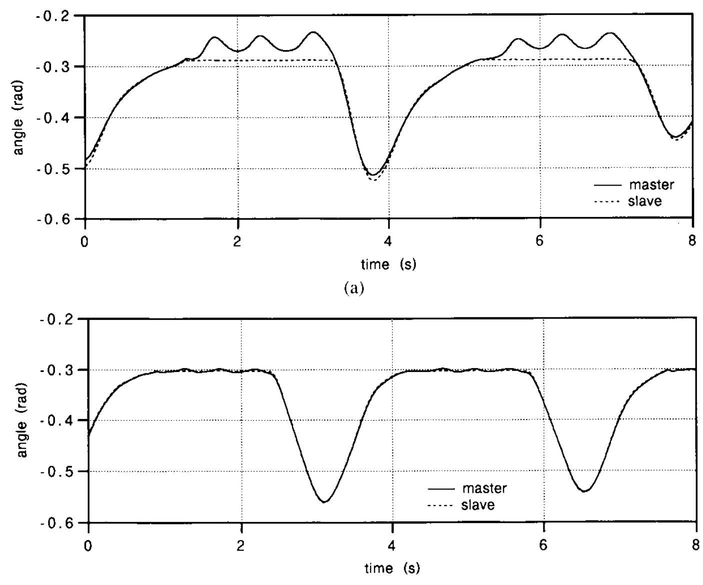

Fig. 12. Experimental results: position responses in Task 2. (a) Conventional force-reflecting servo type. (b) Proposed type with $\kappa = 0.8$.

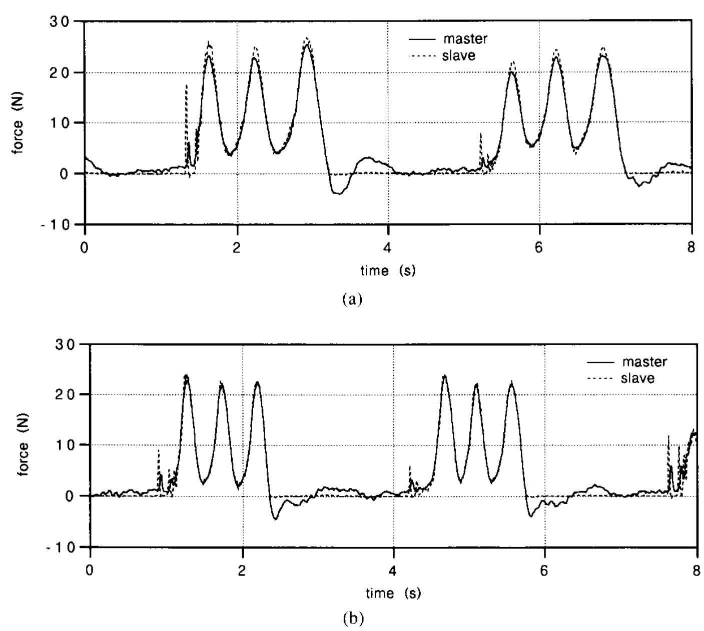

Fig. 13. Experimental results: force responses in Task 2. (a) Conventional force-reflecting servo type. (b) Proposed type with $\kappa = 0.8$.

the remote environment. Applying the control scheme of (65) and (66) corresponds to achieving the state shown in Fig. 5 from the actual system shown in Fig. 1, where the operator and the object are virtually connected by a rigid but weightless bar. However, this state is very critical because only a small error of the inertia parameter may change the massless bar into a bar with negative mass. Here, we try to make the dynamics of master and slave arms act as a certain kind of impedance shown in Fig. 6. Since this impedance seemingly intervenes between the operator and the object, we call it *intervening impedance*. The existence of this intervening impedance makes the system strictly passive, and an appropriate impedance may be able to help the operator in a given task.

The state of Fig. 6 can be described by the following equation by setting $x_m = x_s \triangleq x$:

$$f_m - f_s = \hat{m}\ddot{x} + \hat{b}\dot{x} + \hat{c}x \tag{67}$$

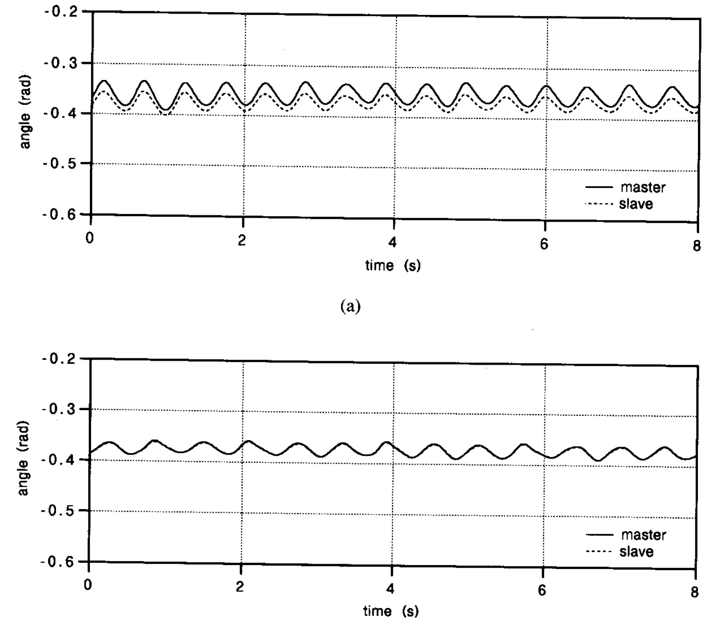

Fig. 14. Experimental results: position responses in Task 3. (a) Conventional force-reflecting servo type. (b) Proposed type with $\kappa = 0.8$.

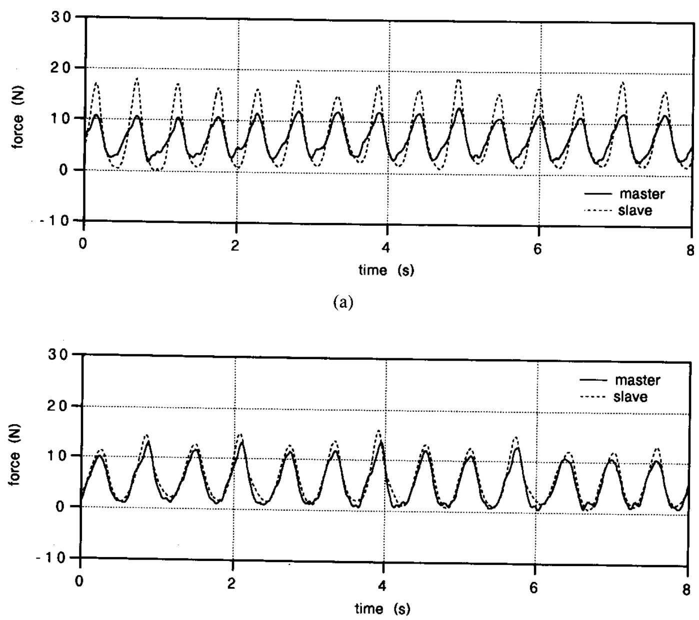

Fig. 15. Experimental results: force responses in Task 3. (a) Conventional force-reflecting servo type. (b) Proposed type with $\kappa = 0.8$.

where $\hat{m}, \hat{b}$, and $\hat{c}$ are the mass, coefficient of viscous friction, and stiffness of the intervening impedance respectively. Since x_m and x_s may not coincide all the time, we consider the following equation instead of (67):

$$f_m - f_s = \hat{m}\ddot{x}_{ms} + \hat{b}\dot{x}_{ms} + \hat{c}x_{ms}. \tag{68}$$

We also set the following equation corresponding to (62):

$$\ddot{e} + k_1\dot{e} + k_2 e = \lambda \frac{f_m + f_s}{2} \tag{69}$$

where $\lambda > 0$ is a positive constant. Substituting new inputs u_m and u_s, which realize (68) and (69), into (53) and (54), respectively, we get the following control scheme:

$$\begin{aligned}\tau_m &= m_m[\ddot{x}_{ms} + k_1(\dot{x}_{ms} - \dot{x}_m) + k_2(x_{ms} - x_m)] \\ &\quad + b_m\dot{x}_m - \frac{(1+k_{mf})}{2}[\hat{m}\ddot{x}_{ms} + \hat{b}\dot{x}_{ms} + \hat{c}x_{ms}] \\ &\quad + \frac{\lambda}{2}m_m f_{ms} - k_{mf}(f_{ms} - f_m) - f_{ms} \qquad (70)\\ \tau_s &= m_s[\ddot{x}_{ms} + k_1(\dot{x}_{ms} - \dot{x}_s) + k_2(x_{ms} - x_s)] \\ &\quad + b_s\dot{x}_s - \frac{(1+k_{sf})}{2}[\hat{m}\ddot{x}_{ms} + \hat{b}\dot{x}_{ms} + \hat{c}x_{ms}] \\ &\quad - \frac{\lambda}{2}m_s f_{ms} + k_{sf}(f_{ms} - f_s) + f_{ms}. \qquad (71)\end{aligned}$$

If we set $\lambda = 0$ in (70) and (71), e converges into zero with appropriate gains k_1, k_2. Therefore, the control scheme of (70) and (71) with $\lambda = 0$ is one of the examples of the control schemes that realize ideal response I. When $\lambda = 0$ and $\hat{c} = 0$, the corresponding intervening impedance can be regarded as a mechanical master-slave manipulator model where the viscous friction of the transmission wires is considered. Moreover, when $\hat{m} = \hat{b} = \hat{c} = 0$ and $\lambda = 0$, this control scheme coincides with that of (65) and (66). In this sense, the control scheme of (65) and (66) is a special case when the intervening impedance is zero.

On the contrary, when $\hat{m} = \hat{b} = \hat{c} = 0$ and $\lambda \neq 0$ in (70) and (71), this control scheme realizes ideal response II.

Consequently, we can regard the control scheme of (70) and (71) as a general form of the control schemes realizing three ideal responses. If we set $\lambda \neq 0$ and $\hat{m}, \hat{b} \neq 0, \hat{c} = 0$, the control scheme cannot realize the ideal response I nor II. However, the corresponding intervening impedance can be a model of mechanical master-slave manipulators where the stiffness of the transmission wires is also considered.

C. Discussion about Stability

In Section V, we have discussed the system stability based on the concept of passivity. In this subsection, we show the passivity of the system when the general form of control scheme in (70) and (71) is applied.

In Section V, we have shown that the passivity of the system can be checked by the scattering matrix. Substituting the parameters of (70) and (71) into (52), we get

$$S = \frac{1}{((s + k_1 + k_2/s) + \frac{1}{2}\lambda)((\hat{m}s + \hat{b} + \hat{c}/s) + 2)} \times \begin{bmatrix}\alpha & \beta \\ \beta & \alpha\end{bmatrix} \qquad (72)$$

where

$$\alpha = (s + k_1 + k_2/s)(\hat{m}s + \hat{b} + \hat{c}/s) - \lambda$$
$$\beta = 2(s + k_1 + k_2/s) - \tfrac{1}{2}(\hat{m}s + \hat{b} + \hat{c}/s).$$

From (72), the singular values of S are given as follows:

$$\sigma_1 = \frac{|(\hat{m}s + \hat{b} + \hat{c}/s) - 2|}{|(\hat{m}s + \hat{b} + \hat{c}/s) + 2|} \le 1 \qquad (73)$$

$$\sigma_2 = \frac{|(s + k_1 + k_2/s) - \frac{1}{2}\lambda|}{|(s + k_1 + k_2/s) + \frac{1}{2}\lambda|} \le 1. \qquad (74)$$

Consequently, the system stability when the proposed control scheme is applied has been guaranteed under the assumption in Section V.

From (73) and (74), both singular values become just 1 when the control scheme of (65) and (66) is applied. This is a critical situation where there is no power consumption in the system. This ideal situation can be realized only when the arm parameters are exactly known and exact signals of position, velocity, acceleration, and force are available without time delay. Therefore, in practical sense, the system may not keep passive unless we set an appropriate intervening impedance. Exact conditions for the intervening impedances to keep passive against time delay and parameter uncertainty should be studied in future.

D. Simulation

In this subsection, we confirm the validity of the proposed control scheme by simulations. We used the same parameters of the master and slave arms and the operator as those in the numerical examples in Section IV. Object 2 in the numerical examples was chosen for the simulation.

The following three control schemes are compared.

Case 1: Force-reflecting servo type:

$$K_{mfm} = 2.5, \quad K_{mfs} = 3.5$$
$$K_{sps} = K_{spm} = 400\,[\mathrm{N/m}], \quad K'_{sps} = 50\,[\mathrm{Ns/m}].$$

Case 2: Proposed scheme (65) and (66):

$$k_1 = 8.0\,[1/\mathrm{s}], \quad k_2 = 70\,[1/\mathrm{s}^2], \quad k_{mf} = k_{sf} = 0.$$

Case 3: Proposed scheme (70) and (71):

$$k_1 = 8.0\,[1/\mathrm{s}], \quad k_2 = 70\,[1/\mathrm{s}^2], \quad \hat{m} = 2.0\,[\mathrm{kg}]$$
$$\hat{b} = 1.0\,[\mathrm{kg/s}], \quad \hat{c} = 0.0\,[\mathrm{kg/s}^2], \quad \lambda = 0.21\,[1/\mathrm{kg}]$$
$$k_{mf} = k_{sf} = 0.$$

Before showing the simulation results, let us evaluate the maneuverability of the proposed schemes by the proposed indices J_p and J_f. Fig. 7 shows the indices of the above three cases. Case 1 has the same gains with the numerical examples in Section IV, and one can compare the performance of the proposed schemes to those of the other conventional schemes in Fig. 4. Since case 2 realizes the ideal response III, both indices are zero for any Z_L.

Fig. 8 shows the responses of x_m, x_s, f_m and f_s, respectively, when a sinusoidal input $\tau_{op} = 5 - 5\cos(4\pi t)$ [N] is exerted. Sampling time is 1 [ms]. In the figure, the maximum actuator inputs max $|\tau_m|$ and max $|\tau_s|$ are shown. While case 1 has errors in both position and force responses, case 2 almost realizes ideal response III. It should be noted that the case 1 becomes unstable with larger gains. Case 3 shows the effect of the intervening impedance. The actuator inputs were reduced due to the existence of the intervening impedance.

VII. Experiment

A. Experimental System

We built a prototype of master-slave system for experiments. Master and slave arms are 3 DOF SCARA-type planar manipulators. All joints are driven by direct-drive DC motors produced by SHINMEIWA Industry Co. Ltd. Arm configurations of master and slave are identical and each link length (link1 = 0.25 [m], link2 = 0.3 [m]) was chosen so that its configuration is equal to the projection of human arm onto the horizontal plane.

We named this experimental master-slave system "RATSUWAN" that means "outstanding ability" in Japanese. Controller is a personal computer with 32-bit CPU 80386/80387 (20 MHz), and the torque command is sent to each motor driver through a D/A converter. Encoder pulse signals (120 000 plus/rev) of each joint can be obtained from an output terminal of each motor driver.

In order to get a sufficient resolution of the joint velocities in wide range, the following two method are combined: 1) counting the number of crystal clock pulses during the interval of the encoder pulses and 2) differentiating the encoder pulse count in each sampling period. Six-axis force/torque sensors produced by OMRON Co. Ltd. are attached at both tips of the arms.

B. Tasks in the Experiment

We used only the elbow joint (joint 2) of each arm in the experiment. The shoulder joint (joint 1) is mechanically fixed, whereas the wrist joint (joint 3) is free so that the operator can always grip the arm tip firmly. Fig. 9 shows the experimental setup with one DOF system.

The following three tasks were carried out.

1) Task 1: The slave arm is free. There are three LED's on a table at the slave side, and they are lighted one-by-one periodically. The operator maneuvers the system so that the tip of the slave arm comes onto the lighted LED.

2) Task 2: An aluminum plate is firmly fixed on the table by cramps. The operator makes the slave arm collide with the plate and push the plate through the system. Since the tip of the slave arm is also made of aluminum, the contact becomes the most critical one, "hard contact" [10].

3) Task 3: A sponge for dishwashing is set at the slave side. The operator pushes the sponge through the system and examines how well he/she can feel the impedance of the sponge.

C. Control Schemes

We chose a typical conventional control scheme, force-reflecting servo type. The control scheme and its gains are given as follows:

1) Force-Reflecting Servo-Type:

$$\begin{aligned} \tau_m &= -f_s - K_f(f_s - f_m) \\ \tau_s &= K_v(\dot{x}_m - \dot{x}_s) + K_p(x_m - x_s) \\ K_v &= 166.7\,[\mathrm{Ns/m}], \quad K_p = 1333.3\,[\mathrm{N/m}] \\ K_f &= 0.3 \end{aligned}$$

where $x_m = l_2 \times \theta_m$ and $x_s = l_2 \times \theta_s$ are equivalent hand tip displacements of the master and slave arms, θ_m and θ_s denote the joint angles, and $l_2 = 0.3$ [m] is the link length. The equivalent driving forces at the tip τ_m and τ_s are finally converted to the joint torques.

The proposed control scheme in Section VI can be represented by the following form:

2) Proposed Type:

$$\begin{aligned} \tau_m &= \kappa\overline{M}\ddot{x}_{ms} + K_v(\dot{x}_s - \dot{x}_m) + K_p(x_s - x_m) - f_{ms} \\ \tau_s &= \kappa\overline{M}\ddot{x}_{ms} + K_v(\dot{x}_m - \dot{x}_s) + K_p(x_m - x_s) + f_{ms} \\ K_v &= 166.7\,[\mathrm{Ns/m}], \quad K_p = 1333.3\,[\mathrm{N/m}] \end{aligned}$$

where $\overline{M}$ is the equivalent mass obtained from the moment of inertia around joint 2 and its identified value is 6.04 [kg], and κ denotes the coefficient of dynamics compensation. The above control scheme corresponds to (70) and (71) when $m_m = m_s = \overline{M}, k_1 = 2K_v/\overline{M}, k_2 = 2K_p/\overline{M}, b_m = b_s = 0, \lambda = 0, k_{mf} = k_{sf} = 0, \hat{m} = 2(\overline{M} - \kappa\overline{M})$ and $\hat{b} = \hat{c} = 0$.

When $\kappa = 1.0$, the above scheme cancels all of the arm dynamics and it realizes the ideal response III. When $0 \leq \kappa < 1.0$, the inertia of $\hat{m} = 2(\overline{M} - \kappa\overline{M})$ intervenes between the operator and remote environment, and ideal response I is realized.

Acceleration signals of the both arms are obtained by numerically differentiating the velocity signals. The differentiated data is passed through a digital filter whose cut-off frequency is 19.8 Hz. Ideally, we can set κ as close to 1.0 as we want. However, $\kappa = 0.8$ was the actual upper bound to keep the good responses due to the delay of acceleration signals. Therefore, we set $\kappa = 0.8$. Sampling time was 1.68 ms for all cases. We cannot guarantee the system passivity with the proposed scheme using filtered accelerations. Consideration of the system passivity with filtered signals remains for future work.

D. Experimental Results and Discussion

Figs. 10 through 15 show experimental results of three tasks by the conventional control scheme and the proposed scheme.

In Task 1, as shown in Fig. 10, position response of the slave arm has over-shoot with respect to that of the master arm when the conventional force-reflecting servo type is applied. In task 1, the force of the master side should be small as much as possible in the sense of ideal response because no external force is applied at the slave side.

In this task, we also show the results when $\kappa = 0.0$ in addition to $\kappa = 0.8$. As shown in Figs. 10 and 11, position responses of the master and slave arms are almost equal with the proposed schemes, since it satisfies the condition of the ideal response I irrespective of the value of κ. When $\kappa = 0.0$, the operator feels the intervening inertia which is twice of the original arm inertia. And the apparent inertia becomes very heavy. However, by canceling the dynamics of the two arms with $\kappa = 0.8$, the force at the master side becomes smaller and the system response becomes closer to the ideal response III.

In Task 2, there is more remarkable difference between the conventional control scheme and the proposed scheme as shown in Figs. 12 and 13. With the conventional scheme, large position error appears when the slave comes into contact with the object. Since the conventional scheme generates the force at the slave side based on the position errors between the master and slave, it is necessary to make the feedback gain infinitely large in order to make the position error zero. Practically, however, large gains may cause instability of the system. In the case of the proposed scheme, the position error between the master and slave arms is almost zero even when the slave arm collides with the object. Consequently, the operator can feel a realistic "rigid wall" with the proposed scheme.

In Task 3, the operator exerted force periodically against the sponge. The results are shown in Figs. 14 and 15. When the proposed scheme is applied, the operator is able to feel a delicate impedance of the sponge.

VIII. Conclusion

The main results of this paper can be summarized as follows:

1) A simple one degree of freedom system model of the master-slave system has been discussed where both the operator dynamics and object dynamics have been taken into account.
2) Three ideal responses have been defined and the conditions to achieve these ideal responses have been derived. A quantitative index of maneuverability has been proposed based on the concept of the ideal responses. For evaluating the maneuverability of the system, parameters of the master and slave arms, parameters of the operator dynamics and the object dynamics are necessary.
3) The stability of the system is discussed based on the concept of network passivity.
4) New control schemes of master-slave manipulators have been proposed which can realize the ideal responses. These control schemes take the arm dynamics into account using acceleration signals. The proposed scheme requires exact parameters of the arm dynamics but parameters of the operator and object are not necessary. It has been shown that the proposed control scheme guarantees the stability under a certain assumption.
5) The proposed control schemes have been implemented with a prototype of master-slave system and the validity of the proposed control scheme has been confirmed.

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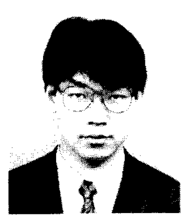

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