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Paper

Impedance controlled master–slave manipulation system. Part 1. Basic concept and application to the system with a time delay

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Abstract—An impedance controlled master–slave manipulation system is proposed for use as part of a tele-existence manipulation system. Tele-existence aims at the natural and efficient remote control of robots by providing a human operator at the controls with the real-time sensation of presence that enables him/her to perform remote manipulation tasks dexterously with the feeling that they exist inside the slave anthropomorphic robot in the remote environment. The proposed system regulates the impedance of the master manipulator and slave manipulator so that they coincide with each other. An impedance model of the remote environment is generated to be used for the control. Four basic impedance controlled master–slave manipulation schemes are applied to the system with a time delay. The feasibility of the proposed method is demonstrated by experiments using a hardware direct-drive master manipulator and a software slave manipulator.

1. INTRODUCTION

Systematic research for the development of tele-existence has been conducted by feeding back rich sensory information which the remote robot has acquired to provide the operator with a real-time sensation of presence [1]. Tele-existence, requires natural feedback methods not only for visual information, but also for kinaesthetic information with which the operator is able to feel the robot arms as his/her own. We have developed a master–slave manipulation system (MSMS) to establish kinaesthetic feedback [2, 3].

Symmetry type, force reflection type, and force feedback type MSMSs are conventional teleoperators. In the symmetry type, both dynamics of the MSMS are added to the reflection force to the operator. In the force reflection type, the dynamics of the master manipulator are added to the reflection force. In the force feedback type, the dynamics of both arms can be erased when the force feedback gain is set at an infinite value. But the system may become unstable if the gain is sufficiently large. In each type, the dynamics of the master–slave arms are fixed (see Appendix A).

Regulation of the arm dynamics of the MSMS is effective to give a teleoperator a real sensation of presence. Recently several bilateral manipulation methods have been studied. Bilateral manipulation with adaptive control as an extension of conventional bilateral methods has been proposed by Fukuda [4]. Furuta and Kosuge [5] applied the virtual model following control to MSMS to regulate the arm dynamics. Yoshikawa and Yokokoji [6, 7] formulated the ideal response of an MSMS in which the operator feels the direct manipulation of the target, and proposed a dynamic control method to remove the dynamics of both the master and the slave arms while retaining force and motion information. Also, adaptive control of the MSMS to the object dynamics as the target model of each arm has been proposed [8, 9]. In the ideal response scheme and model following control method, although it is ideal for tele-existence that both the position and the force responses of the master and slave manipulators are exactly the same regardless of the object dynamics, it is physically unrealizable because this condition requires the complete elimination of the master and slave manipulator dynamics, which means that the total dynamics characteristic must be zero, including zero mass. The MSMS may become unstable because of impossible regulation of the control system to erase both arm dynamics, especially the inertia of the arms [10, 11]. Therefore, other stable control methods were proposed with impedance between the master and slave [10, 12]. Thus, the technique of manipulation tele-existence has developed with the formulation of the real sensation of telemanipulation, the design and dynamic control of the arm dynamics, and adaptive control to the object model.

However, since the arm dynamics are fixed to some regulated values in these MSMS methods, there are no mechanisms for changing the dynamics of the arm as desired according to the task and operation environment. Also, the earlier methods cannot be extended to a system in which the variable dynamics of the MSMS are utilized for operational capability.

It is necessary, for tele-existence MSMSs, to maintain flexibility in the choice and design of the known dynamics. A flexible MSMS is required to adapt to various kinds of task and to its environment. Also, since the earlier MSMSs needed a lot of information communicated between the master and slave systems, the control scheme should be as simple as possible, and the amount of information exchanged between the master and slave systems should be as small as possible. These conditions are important, especially in the implementation of a real system.

In this paper, an impedance controlled master–slave manipulation method is proposed for use in tele-existence. The purpose of the MSMS is to construct a system provided with the direct manipulation sensation and the extension of the operation capability for more operator-friendly manipulation sensation. Also, the proposed scheme is a generalized method of conventional ones, and it can be extended to realize various kinds of manipulation sensation. For instance, the MSMS is applied to a system with a time delay.

The paper is organized as follows. In Section 2, the principle of impedance controlled MSMS is presented in *physical equivalence*, which means the same size, the same velocity motion, the same input/output force conditions, and no time delay condition. It is shown that the proposed method is a generalized method of conventional ones and it provides a high real sensation of presence. In Section 3, a model-based impedance controlled MSMS is also proposed. In Section 4, the proposed MSMS can adapt to a very long time delay. In Section 5, some experimental results to verify the proposed scheme are explained.

2. PRINCIPLE OF THE IMPEDANCE CONTROLLED MASTER–SLAVE MANIPULATION SYSTEM

In this section, the principle of the proposed impedance controlled MSMS is explained in physical equivalence (the master and slave arms have the same configuration, motion velocity, and input–output force conditions), and it is shown that the proposed system is a generalized method of the bilateral MSMS and provides a real sensation of presence.

2.1. Control method of impedance controlled MSMS

The proposed MSMS is a system in which the dynamics of the manipulators and their environments are defined as mechanical impedance models, and the models are regulated to extend the operator capability. We call the MSMS an impedance controlled master–slave manipulation system in which impedance control is applied to construct the fundamental part of the MSMS.

Impedance control deals with the dynamic interaction between a robot and its environment. The manipulator can execute a stable force control in contact with an object by the control method [13, 14]. When performing a contact task, the relationship between the robot and its environment is defined as mechanical impedance; their dynamic interaction is considered to be the change of the impedance. The regulation appears as a change of the robot's apparent dynamics (inertia, viscosity, and stiffness). The fundamental concept of the control is that the control target is not only the dynamics of the robot, but also the integrated dynamics of the robot and its environment. The concept can be applied to a scheme to deal with the identification of an unknown object's dynamics, or to the creation of an environment with apparently regulated dynamics. These applications need an integrated control scheme for the 'robot + environment'. Therefore, it is also effective for the MSMS dealt with in this paper.

The proposed impedance control of an MSMS in the physically equivalent, no time delay conditions which are basic requirements of our target concept of a tele-existence manipulator can be classified into four basic types according to the type of information exchanged between the master and slave. In the *dual force transmission method (D-F)*, the master manipulator transmits the human master's operational force to the slave manipulator, while the slave transmits the reaction force from the environment to the master manipulator. The *motion force transmission type (M-F)* transmits the master's motion to the slave, and the force from the slave to the master. In the *force motion transmission type (F-M)*, the master's force and the slave's motion are exchanged. The *dual motion transmission type (D-M)* exchanges motions of both the master and the slave.

Assume that the master and slave arms have the same dynamics or the dynamics are made equivalent by impedance control. The equation of motion of the master manipulator and the master slave control strategy can be described as follows (for the generalized case with consideration of the operator dynamics, see Appendix B):

$$F_0 = M_0\ddot{X}_m + B_0\dot{X}_m + K_0X_m - F_1, \quad (1)$$

$$F_1 = C_1. \quad (2)$$

The equation of motion of the slave manipulator, and the master slave control strategy are

$$F_2 = M_0\ddot{X}_s + B_0\dot{X}_s + K_0X_s + F_e, \tag{3}$$

$$F_2 = C_2. \tag{4}$$

The equation of motion of an object is described as

$$F_e = M\ddot{X}_s + B\dot{X}_s + K\,\delta X_s, \tag{5}$$

where (M_0, B_0, K_0) are the impedance parameters of the master and slave arms, and (M, B, K) are the mechanical impedance parameters of the object. F_0 denotes the force exerted by the human operator. F_1 is the inner force of the master manipulator and F_2 that of the slave manipulator; F_e indicates the reflection force from the object. X_m and X_s denote the position vectors of the master and slave, respectively, and δX_s is the position deviation vector of the object. The choice of C_1 and C_2 determines the types of impedance controlled master–slave scheme. Each parameter of the impedance is a 6×6 matrix. Each position and posture of X_m and X_s, and each force of F_0, F_1, F_2, and F_e is a 6×1 vector.

(1) In the D-F type, the operation force of the master and external force of the slave are transmitted to each other. Each force is detected by a force/torque sensor mounted on each arm. The operation force and reflection force are translated to the slave and master inner torque, respectively. The control scheme C_1 and C_2 are set as follows:

$$C_1 = -F_e, \tag{6}$$

$$C_2 = F_0. \tag{7}$$

By use of the scheme, from equations (1)–(4), (6), and (7), the positional error $e = X_m - X_s$ can be represented by the equation

$$M_0\ddot{e} + B_0\dot{e} + K_0e = 0. \tag{8}$$

The error e can be reduced to zero by appropriately selecting the mechanical impedance parameters (M_0, B_0, K_0), and X_m becomes equal to X_s, which can be described as X. From equations (1), (3), and (5), the relationship between the operational force and the reaction force becomes

$$\begin{aligned} F_0 &= (M_0\ddot{X} + B_0\dot{X} + K_0X) + F_e \\ &= (M_0\ddot{X} + B_0\dot{X} + K_0X) + (M\ddot{X} + B\dot{X} + K\,\delta X). \end{aligned} \tag{9}$$

If we select an appropriately small and known target impedance, F_0 becomes very similar to F_e, and the operator can feel the object as closely as in direct manipulation while knowing the exact residual dynamics—ideal for tele-existence [7] (see Fig. 1a).

(2) The M-F type transmits the master's motion to the slave, and the force from the slave to the master. This type can be described by setting C_1 and C_2 as follows:

$$C_1 = -F_e, \tag{10}$$

$$= M_0\ddot{X}_m + B_0\dot{X}_m + K_0X_m. \tag{11}$$

From equations (1)–(5), (10), and (11), the reflection between the operational force and reaction force is described by the following equations (see Fig. 1b):

$$F_0 = (M_0\ddot{X}_m + B_0\dot{X}_m + K_0X_m) + F_e$$
$$= (M_0\ddot{X}_m + B_0\dot{X}_m + K_0X_m) + (M\ddot{X}_s + B\dot{X}_s + K\,\delta X_s), \tag{12}$$

or

$$F_0 = (M_0\ddot{X}_m + B_0\dot{X}_m + K_0X_m) + (M_0\ddot{e} + B_0\dot{e} + K_0e), \tag{13}$$

$$F_e = M_0\ddot{e} + B_0\dot{e} + K_0e. \tag{14}$$

(3) In the F-M type, the master's force and the slave's motion are exchanged. This type can be realized by applying the following C_1 and C_2:

$$C_1 = M_0\ddot{X}_s + B_0\dot{X}_s + K_0X_s, \tag{15}$$

$$C_2 = F_0. \tag{16}$$

From equations (1)–(5), (15), and (16), the relationship between the operational force and reaction force becomes (see Fig. 1c):

$$F_0 = (1/2)\{(M_0\ddot{X}_m + B_0\dot{X}_m + K_0X_m) + F_e\}$$
$$= M_0\ddot{e} + B_0\dot{e} + K_0e, \tag{17}$$

$$\mathrm{F_e} = (M_0\ddot{e} + B_0\dot{e} + K_0e) - (M_0\ddot{X}_s + B_0\dot{X}_s + K_0X_s). \tag{18}$$

(4) In the D-M type, which transmits each motion to each other, C_1 and C_2 are set as follows:

$$C_1 = M_0\ddot{X}_s + B_0\dot{X}_s + K_0X_s, \tag{19}$$

$$C_2 = M_0\ddot{X}_m + B_0\dot{X}_m + K_0X_m. \tag{20}$$

From equations (1)–(5), (19), and (20), the relationship between the operational force and reaction force is described as

$$F_0 = F_e = M_0\ddot{e} + B_0\dot{e} + K_0e$$
$$= M\ddot{X}_s + B\dot{X}_s + K\,\delta X_s. \tag{21}$$

In the method, both systems transmit motion information to each other without force/torque sensors. From equation (21), if the operator does not operate the master arm, then $F_0 = F_e$. If we select (M_0, B_0, K_0) appropriately, then $e \to 0$. In the case where the operator manipulates the master arm or the slave arm, then $e \neq 0$, and the operation and external force are proportional to the difference in the master and slave motion. Therefore, the MSMS may become unstable by the forced oscillation with $F_0 = F_e$. However, the system becomes stable by the modified control scheme including the object dynamics shown in Section 3.2 (see Fig. 1d).

2.2. *Characteristics of impedance controlled MSMS*

The proposed MSMS controls the dynamics of each arm directly and independently. In the fundamental mode of the MSMS, the regulated impedances are coincident. Physically, the operator is given the sensation of manipulating an

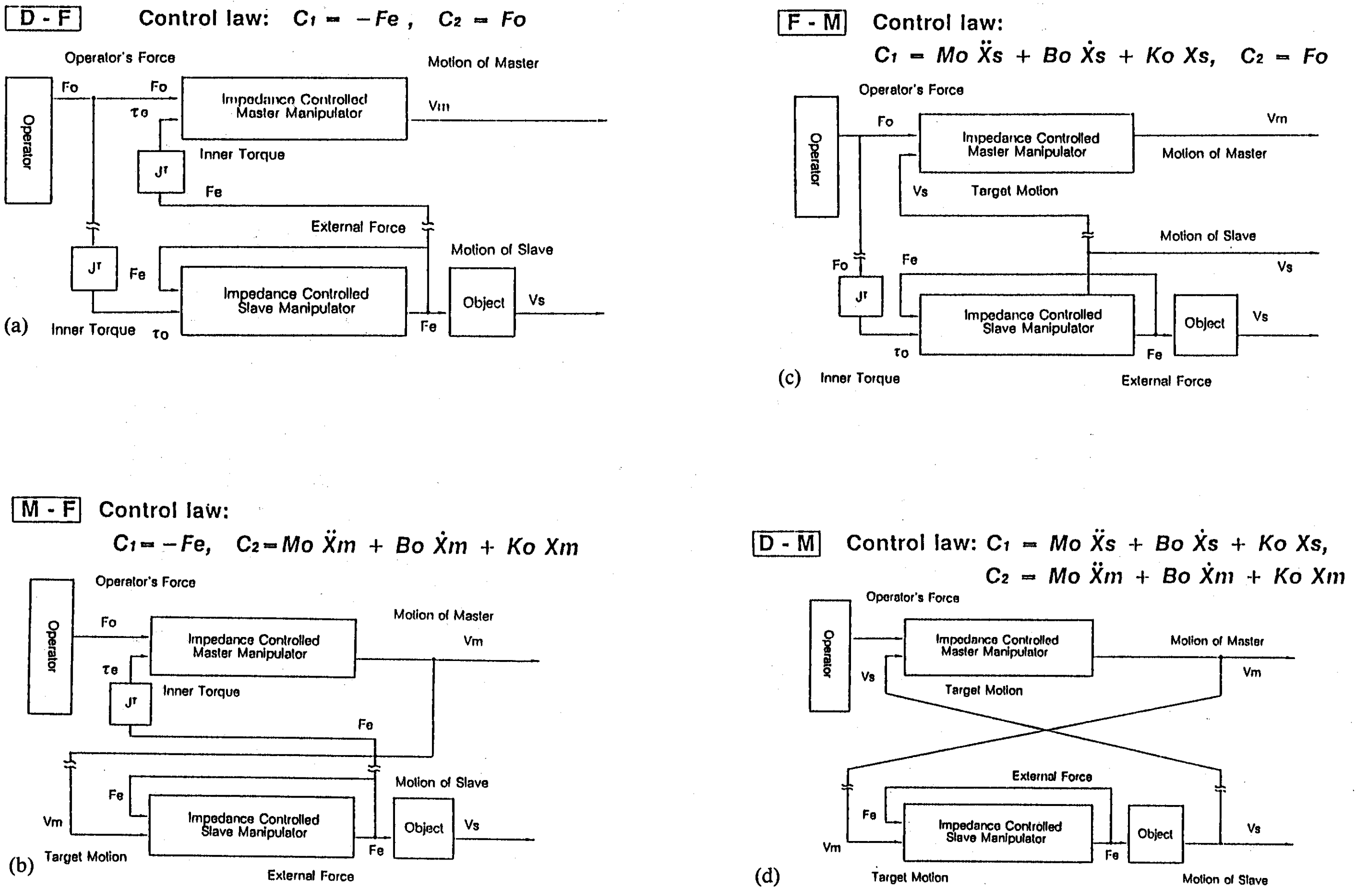


Figure 1. Impedance controlled master–slave manipulation system. (a) D-F type impedance controlled MSMS; (b) M-F type impedance controlled MSMS; (c) F-M type impedance controlled MSMS; (d) D-M type impedance controlled MSMS.

object with a small residual impedance ball, whose weight is compensated, mounted on his/her hand. If the residual impedance is sufficiently small and invariant, the operator can receive the sensation of approximately direct manipulation of the object. Also, the amount of information transmitted between the master and slave systems, which is either force or motion information, is less than that of conventional MSMSs. In addition, some schemes of the proposed MSMS do not require any force/torque sensors. In the MSMS, the operator can operate the slave manipulator according to the master manipulator motion, and he/she can get the real sensation of object manipulation. In this section, the target impedance of the arms and the relationship among the proposed schemes are discussed.

When the actuator output capability is sufficient, the residual impedance parameters (M_0, B_0, K_0) can be selected to satisfy the critical damping condition to ensure stability from equation (8), and to be diagonal for each parameter matrix, then,

$$(M_0^{-1}B_0)^2 - 4M_0^{-1}K_0 = 0. \tag{22}$$

The root s of the characteristic equation is given by the following equation:

$$\det\{sI + (1/2)M_0^{-1}B_0\} = 0. \tag{23}$$

The diagonal impedance parameters (M_0, B_0, K_0) are selected to set the root λ_i $(i = 1, \ldots, 6)$ as sufficiently large and negative as possible in the actuator output torque capability.

In addition, from equation (9), the target impedance is required to be as small as possible for the master operation capability and reflection response in the D-F type. We define the target impedance as follows:

$$Z(s) = M_0 s + B_0 + (1/s)K_0. \tag{24}$$

The norm of the impedance is defined as

$$N[Z(s)] = \sqrt{\mathrm{tr}[Z(s)^{\mathrm{T}}Z(s)]}. \tag{25}$$

Define the eigenvector V_i $(i = 1, \ldots, 6)$ of the root λ_i of the above characteristic equation, and let $T = [V_1 \ldots V_6]$. Also let $A = -(1/2)M_0^{-1}B_0$. This norm has the following relationship:

$$T^{-1}AT = \begin{vmatrix} \lambda_1 & & 0 \\ & \ddots & \\ 0 & & \lambda_6 \end{vmatrix} = \Lambda. \tag{26}$$

From the specification of a norm,

$$\begin{aligned} N[sI - A] &= N[TT^{-1}(sI - A)TT^{-1}] \\ &= N[T(sI - \Lambda)T^{-1}] \\ &\leqslant N[T]\,N[T^{-1}] \\ &\quad \times \sqrt{(s-\lambda_1)^2 + \cdots + (s-\lambda_6)^2}, \end{aligned} \tag{27}$$

or

$$N[Z(s)] \leqslant |1/s|\, N[M_0] N[sI - A]^2 \leqslant |1/s|\, N[M_0]\, N[T]^2 N[T^{-1}]^2 \times \{(s - \lambda_1)^2 + \cdots + (s - \lambda_6)^2\}. \tag{28}$$

Therefore, it is necessary that the norm of the inertia matrix $N[M_0]$ be sufficiently small in order to set $N[Z(s)]$ as a small value, if the real part of each root λ_i ($i = 1, \ldots, 6$) is a large negative value. The smaller $N[M_0]$ set is, the closer the system response becomes to the ideal bilateral response. The ideal response is the case where $N[M_0]$ is zero.

In addition, the other three MSMS types which have been explained in Section 2.1 may become unstable if either the object oscillates in the resonant frequency of the slave arm or if the operator operates the master arm in the resonant frequency of the master arm, because force information is not detected by

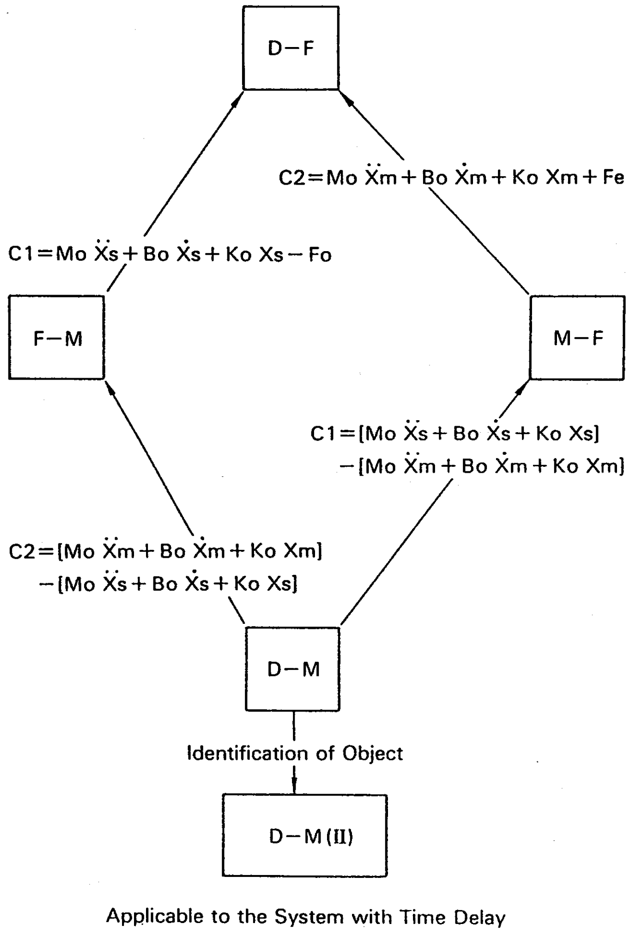


Figure 2. Classification of impedance controlled MSMS.

Table 1.
Classification of impedance controlled MSMS

Information	Method D-F	M-F	F-M	D-M
Forces (both sides)	•	▲	▲	×
Force and motion	▲	•	•	▲
Motions (both sides)	×	▲	▲	•

•: Can be realized without transformation of the control equation.
▲: Can be realized by transforming the control equation.
×: Cannot be realized.

the force/torque sensor in these schemes. However, all the MSMSs expect the D-M type can be transformed into the D-F type by estimating the force information [2].

From equations (13) and (14), the M-F type may become unstable by the reflection from the object. The M-F scheme can be transformed into the D-F scheme by estimating the force F_e and by changing equation (11) to

$$C_2 = M_0\ddot{X}_m + B_0\dot{X}_m + K_0X_m + F_e. \tag{29}$$

The F-M type is stable if the master is not operated or if $e \to 0$ shown in equations (7) and (8), while the system may become unstable if the master is operated, or if $e \neq 0$. In these cases, B_0 must be sufficiently large to prevent such instability. Similarly, from equations (17) and (18), the F-M scheme can be transformed into the D-F scheme by estimating the force F_0 and using equation (30) instead of (15)

$$C_1 = M_0\ddot{X}_s + B_0\dot{X}_s + K_0X_s - F_0. \tag{30}$$

In the transformation, the relationship between the operation and reflection force is similar to that shown in equation (9). The system is equivalent to the D-F type, and the stability is proved.

The D-M scheme can be transformed into either M-F or F-M, but it cannot be transformed into D-F. However, by using the environment and object models discussed in Section 3, each type becomes equivalent to D-F and adaptable to the system with a time delay.

It is also shown that the proposed MSMS type without a force/torque sensor mounted on either the master or slave arm is as efficient as the other proposed MSMS types with sensors mounted on both arms. The relations among the impedance controlled MSMSs are shown in Fig. 2 and Table 1.

3. MODEL-BASED IMPEDANCE CONTROLLED MSMS

In this section, the construction of the impedance controlled MSMS and its application to a system with a time delay by object model identification are discussed.

3.1. System construction

The construction of the proposed MSMS in the tele-existence mode using impedance control is shown in Fig. 3. The master system transmits the master manipulator motion operated by the human operator. The slave system executes a task according to the transmitted information, while the master system reflects the external force to the operator by measuring or estimating it with the transmitted information by the slave. The environment in which the slave arm executes a task on an object is called the task environment. In the master system, the model constructed with task environment information is called the operation environment.

The hardware is composed of the master and slave systems. The arm of each system is controlled by the computer of the system. The sensor in the arm feeds the sensor information of the arm motion to the computer, which commands the output torque to the arm controller. The computer also controls the arm controller and environment simulator. The controller directly commands the output torque to the arm. The environment simulator creates the environment model automatically or by the operator's command. Each system communicates information about the arm motion/force to each other.

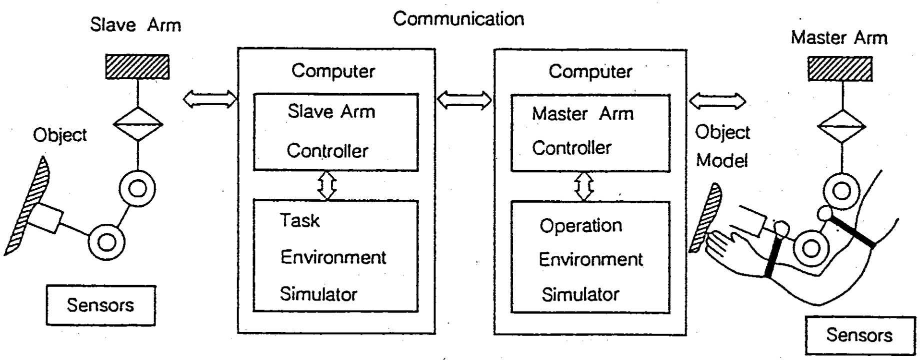


Figure 3. Hardware concept of impedance controlled MSMS.

3.2. Identification of an unknown object's dynamics

When we think about the use of tele-existence in a situation where the master and slave are far apart, perhaps on different planets, it is quite effective to use a realistic model of the environment, including objects and robots, i.e. the use of virtual environments. In other words, the slave system identifies the environment impedance by the slave arm motion, and the master system constructs the slave environment model using the impedance parameters.

In the following case, we assume that the dynamics of each arm are known. A slave arm for which the target impedance is set low, executes a contact task in the task environment autonomously or by the operator's command and generates a small reflection force. The impedance of the task environment is identified by detecting the difference between the real task environment impedance and the assumed one. In other words, the method is similar to the case where a human in a dark room where he/she can see nothing detects a wall by moving his/her arm until contact is made. The dynamics of the manipulator, which are identified [2] before the environment identification, are a measure of the task environment impedance.

In the general case where the impedance parameters ($M_{obj}, B_{obj}, K_{obj}$) are unknown, the method of identifying the parameters is executed as follows. The manipulator equation of motion is given by

$$I\ddot{\Theta} + D_v\dot{\Theta} = T_a + J^T F_e, \tag{31}$$

where I and D_v are the inertia and viscosity matrices of the manipulator, T_a is the actuator output torque vector, F_e is the external force vector, Θ is the rotational angle vector, and J^T is the transposed Jacobian matrix, respectively.

We define the manipulator target impedance $Z(s)$ as follows:

$$Z(s) = M_d s + B_d + (1/s)K_d. \tag{32}$$

From equation (32), the apparent equation of motion of the manipulator is represented as

$$F_e = M_d(\ddot{X} - \ddot{X}_0) + B_d(\dot{X} - \dot{X}_0) + K_d(X - X_0), \tag{33}$$

where $[\ddot{X}_0 \dot{X}_0 X_0]^T$ indicates the target motion of the manipulator. The desired impedance of equation (32) is realized by applying the actuator torque represented as

$$\begin{aligned} T_a = (I - J^T M_d J)\ddot{\Theta} + (D_v - J^T M_d \dot{J} - J^T B_d J)\dot{\Theta} \\ + J^T\{M_d\ddot{X} + B_d\dot{X} + K_d(X_0 - L(\Theta))\}, \end{aligned} \tag{34}$$

where $X = L(\Theta)$.

First of all, in the case where the object dynamics represent a spring with unknown stiffness, the manipulator stops at the point X_e between the commanded equilibrium point X_0 and the contact point X_c to the object. In this case, the manipulator apparently gives the following reflection force F_m to the object:

$$F_m = K_d(X_0 - X_e). \tag{35}$$

Also, the object motion by the force F_m given by the manipulator is

$$F_m = K_{obj}(X_e - X_c). \tag{36}$$

From equations (35) and (36), the object stiffness K_{obj} is calculated as

$$K_{obj} = K_d(X_0 - X_e)(X_e - X_c)^{-1}. \tag{37}$$

Second, consider the case where the manipulator motion velocity is constant, which means that the motion acceleration is zero if the manipulator exerts the contact task to the object. Let the actual velocity of the manipulator motion be $\dot{X}_e$ to the external force F_m.

$$F_m = D_d(\dot{X}_0 - \dot{X}_e) + K_d(X_0 - X_e). \tag{38}$$

Also, when the velocity $\dot{X}_c$ before contact is given,

$$F_m = D_{obj}(\dot{X}_e - \dot{X}_c) + K_{obj}(X_e - X_c). \tag{39}$$

From equations (37)–(39), the object viscosity D_{obj} is given as

$$D_{obj} = \{D_d(\dot{X}_0 - \dot{X}_e) + K_d(X_0 - X_e) - K_{obj}(X_e - X_c)\}(\dot{X}_e - \dot{X}_c)^{-1}. \quad (40)$$

Similarly, the object inertia M_{obj} is calculated as

$$M_{obj} = \{M_d(\ddot{X}_0 - \ddot{X}_e) + D_d(\dot{X}_0 - \dot{X}_e) + K_d(X_0 - X_e) - D_{obj}(\dot{X}_e - \dot{X}_c) - K_{obj}(X_e - X_c)\}(\ddot{X}_e - \ddot{X}_c)^{-1}. \quad (41)$$

Although the object impedance parameters are calculated step by step in the above case, this method can be expanded to the estimation of all parameters in one step, for instance, by the step response. Also, the contact velocity should be zero for precise estimation [15].

3.3. Construction of the operation environment model

In this section, the construction of the master operational environment model applied by the slave task environment model is described.

The mechanical impedance model of the environment is represented as a hexad of the three positional impedances and the three rotational impedances as a function of the three-dimensional position X as follows:

$$Z(X) = [z_{p1}, z_{p2}, z_{p3}, z_{r1}, z_{r2}, z_{r3}]^T. \quad (42)$$

The task and operator environments are different in their scale, the point of origin, and the axis direction in the coordinate systems. Therefore, in order to move the arms with an equivalent target impedance, the coordinate systems are connected by one-to-one mapping to coincide with the coordinate impedance (vector).

We define the following mapping Γ. Γ indicates linear transformation from a task environment coordinate to an operation environment coordinate. The mapping is composed of the coincident operation of origins TRNS($\cdot$), the coincident operation of axes ROT($\cdot$), and the scaling operation SCL($\cdot$). Therefore, Γ is described as

$$\Gamma(\cdot) = \mathrm{SCL}(\mathrm{ROT}(\mathrm{TRNS}(\cdot))). \quad (43)$$

We define the coincidence of the task environment and operation environment as follows:

$$Z_t(X_t) = Z_0(X_0), \quad (44)$$

where Z_t and Z_0 indicate the impedance of the position and posture X_t of the task environment model coordinate system, and the impedance of the position and posture X_0 of the operation environment model coordinate system corresponding to X_t, respectively,

$$X_0 = \Gamma(X_t). \quad (45)$$

Therefore, the communication of the master manipulator motion V_m to the slave system after the mapping of both environment models makes the slave manipulator move along the target motion V_s with the target impedance the same as the master one. The target motion of the slave is given as follows. Let the master arm motion be

$$V_m = [\mathrm{d}^2(X_m)/\mathrm{d}t^2 \ \mathrm{d}(X_m)/\mathrm{d}t \ X_m]^T. \quad (46)$$

Then

$$V_s = \Gamma^{-1}(V_m)$$
$$= [d^2(\Gamma^{-1}(X_m))/dt^2 \; d(\Gamma^{-1}(X_m))/dt \; \Gamma^{-1}(X_m)]^T. \tag{47}$$

The environment model is composed of the apparent models of the manipulator and the task environment. The model does not appear to the operator as an 'operator's hand + manipulator model' + 'environment', but as an 'operator's hand' + 'manipulator model + environment'. Therefore, the operator can get the feeling of touching the 'virtual environment' directly.

3.4. Presentation of a real sensation of presence using the object impedance model

The proposed MSMS can identify its object dynamics with the method described in the previous section. The MSMS presents a real sensation of presence to manipulate the object utilizing the identified model.

For instance, the control schemes (2) and (4) explained in Section 2.1 for the D-M type are modified as

$$C_1 = (M_0\ddot{X}_s + B_0\dot{X}_s + K_0X_s) - \alpha_1, \tag{48}$$

$$C_2 = (M_0\ddot{M}_m + B_0\dot{X}_m + K_0X_m) + \alpha_2. \tag{49}$$

The object model shown in Section 3.3 is described as

$$\alpha_1 = \alpha_2 = M_{obj}\ddot{X}_m + B_{obj}\dot{X}_m + K_{obj}\;\delta X_m, \tag{50}$$

and we combine it with the control schemes (48) and (49). If we set appropriate target impedance parameters (M_0, B_0, K_0) for the critical damping condition from equations (48) and (49), we obtain the following system equation:

$$M_0\ddot{e} + B_0\dot{e} + K_0e = 0. \tag{51}$$

Under this condition we get approximately $X_m = X_s \to X$. The relationship between the operation and reflection force is given as

$$F_0 = F_e = M_{obj}\ddot{X} + B_{obj}\dot{X} + K_{obj}\;\delta X. \tag{52}$$

Therefore, the operator can get the real sensation of presence as the direct manipulation of objects. This scheme is an extended system of the impedance controlled MSMS (D-M type shown in Fig. 1d). Similar extension of the other types of impedance controlled MSMS can also be realized.

4. EXTENSION TO THE SITUATION WITH A VERY LONG TIME DELAY

If we consider a MSMS in a situation where the master and the slave are far apart, the time delay between the systems is quite long. In particular, it is difficult for the master system to control the slave robot with a feedback loop between them. The operator must move the master arm as slowly as possible for stability. Kotoku and Tanie [16] proposed that the MSMS use visual feedback constructed by an environment model. However, in this system a modelling scheme has not yet been established to make a master environment model. Also Anderson and Spong [17] proposed a MSMS scheme which is effective for stable control with a relatively short time delay by the active control of the transmission between the master and slave systems. However, when the time delay becomes long, the MSMS may become unstable.

In this section, the fundamental impedance controlled MSMS is extended to the system to adapt an arbitrary time delay by utilizing the object impedance model described in Section 3. The model is included in the control scheme to operate the arm apparently without a time delay.

We define the time lag as t_d. The relationship between the motion of the master and its delayed motion is

$$\mathbf{X}_m(t) = X_m(t - t_d). \tag{53}$$

From schemes (48) and (49), the schemes can be changed for the system with a time delay as follows:

$$C_1 = (M_0\ddot{X}_m + B_0\dot{X}_m + K_0X_m) - (M_{obj}\ddot{X}_m + B_{obj}\dot{X}_m + K_{obj}X_m), \tag{54}$$

$$C_2 = (M_0\ddot{\mathbf{X}}_m + B_0\dot{\mathbf{X}}_m + K_0\mathbf{X}_m) + (M_{obj}\ddot{\mathbf{X}}_m + B_{obj}\dot{\mathbf{X}}_m + K_{obj}\mathbf{X}_m). \tag{55}$$

Therefore, the relationship of the operation and reflection force is

$$F_0 = M_{obj}\ddot{X}_m + B_{obj}\dot{X}_m + K_{obj}\ \delta X_m, \tag{56}$$

$$\begin{aligned} F_e &= M_{obj}\ddot{\mathbf{X}}_m + B_{obj}\dot{\mathbf{X}}_m + K_{obj}\ \boldsymbol{\delta}\mathbf{X}_m \\ &= M_{obj}\ddot{X}_s + B_{obj}\dot{X}_s + K_{obj}\ \delta X_s. \end{aligned} \tag{57}$$

Since $\mathbf{e} = \mathbf{X}_m - X_s$ and $\mathbf{e} \rightarrow 0$, the slave manipulator moves with the time delay t_d behind the master operation. Let the relationship of the delayed motion be $X = X(t - t_d)$. The external force transmitted to the master is described as

$$F_e = M_{obj}\ddot{\mathbf{X}} + B_{obj}\dot{\mathbf{X}} + K_{obj}\mathbf{X}. \tag{58}$$

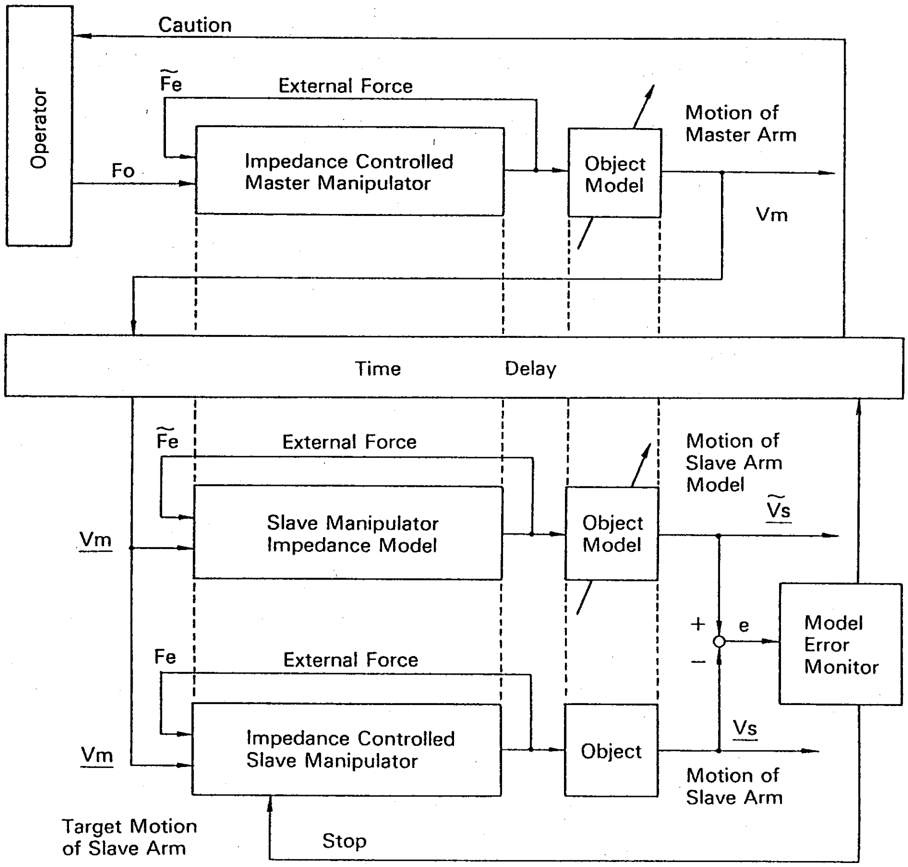
Therefore, the relationship of the operation and external force is (see Figs 2 and 4)

$$F_0(t - t_d) = F_e(t). \tag{59}$$

In this scheme, a human operator works with the master manipulator with force feedback from the model in a virtual environment, which is represented by a mechanical impedance model. Therefore, when there is a time delay t_d between the master and slave systems, the slave arm control lags the master operation by the time delay, while the operator can get the real time sensation of the reflection force directly from the master environment model without any time delay.

This system can also be adapted to the case with a very long time delay by using object models.

The same model is provided on the slave side. The transmitted information of the master's motion or operational force is applied to both the model and the real slave manipulator, and their responses are monitored. The motion of the slave arm model and the real slave are compared, and when the error exceeds a certain limit, the system stops, and a caution signal is sent to the operator with information regarding when and under what conditions it stopped. It will then come back to the



Notes: $\tilde{F}e$ indicates external force from the object model.

$\underline{\tilde{V}s}$ shows motion of slave arm model.

Figure 4. Implementation of the model-based MSMS using the D-M impedance control scheme.

environment identification phase again. After re-identification, the operator backs up and starts his/her task through the virtual environment from the point where the system failed. This flow is shown in Fig. 5.

5. CONTROL EXPERIMENTS

5.1. Experimental hardware

A direct-drive manipulator with three degrees of freedom, a precise mathematical model of which had been acquired, was used as the master manipulator [2, 6]. Each joint of the manipulator was driven by a direct-drive DC motor (Inland) [18] and an encoder of 2000 P/R with a four-times frequency multiplier, which was applied to an up–down counter to estimate the rotational angle. A microprocessor calculated the necessary torque to attain the desired impedance, the outputs of

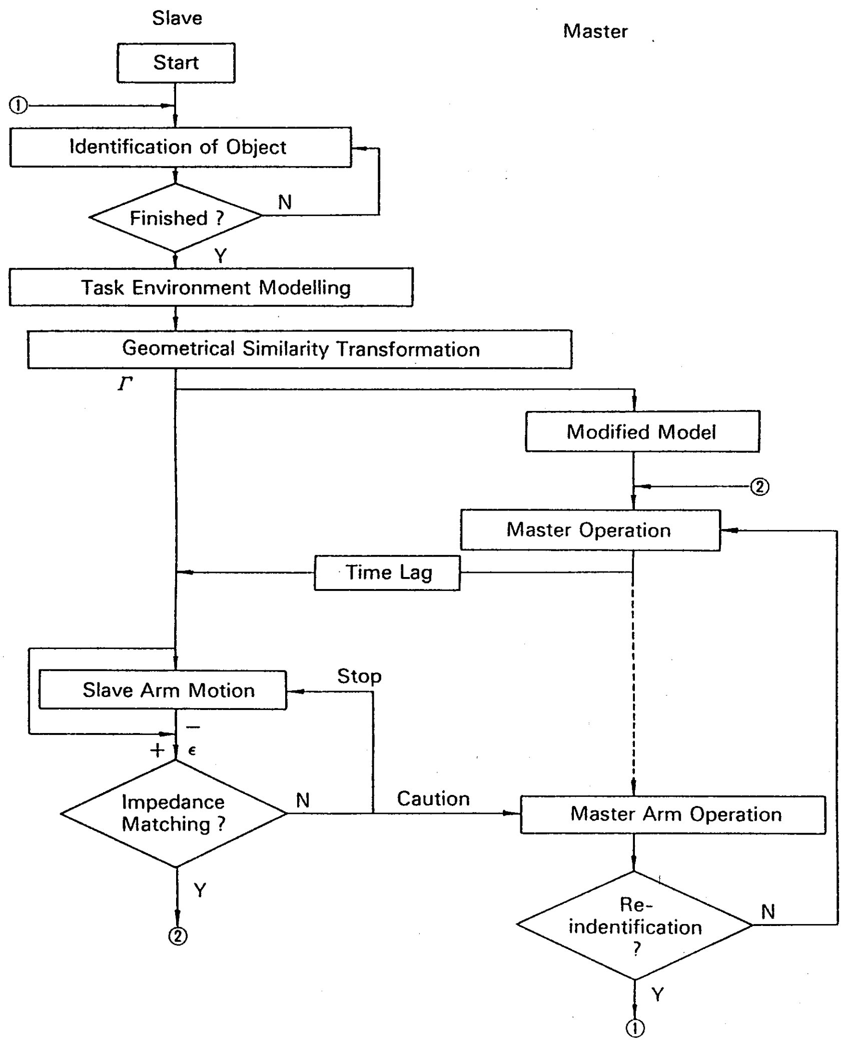


Figure 5. Operation flow of the impedance controlled MSMS for the system with a time delay.

which were applied to servo-amps to control the manipulator. A program was written in C language and the cycle time was less than 3 ms.

The mechanical impedances of the two degrees of freedom of the manipulator (x and y directions) were controlled in the experiment. The slave manipulator and the object were simulated by a dynamic model in a computer. Impedances were assigned for the master manipulator, slave manipulator, and the object. Models of the manipulator and the object were given to the computer. A human subject operator operated the master manipulator, and dynamic responses of the master and slave manipulators were measured under several operational schemes.

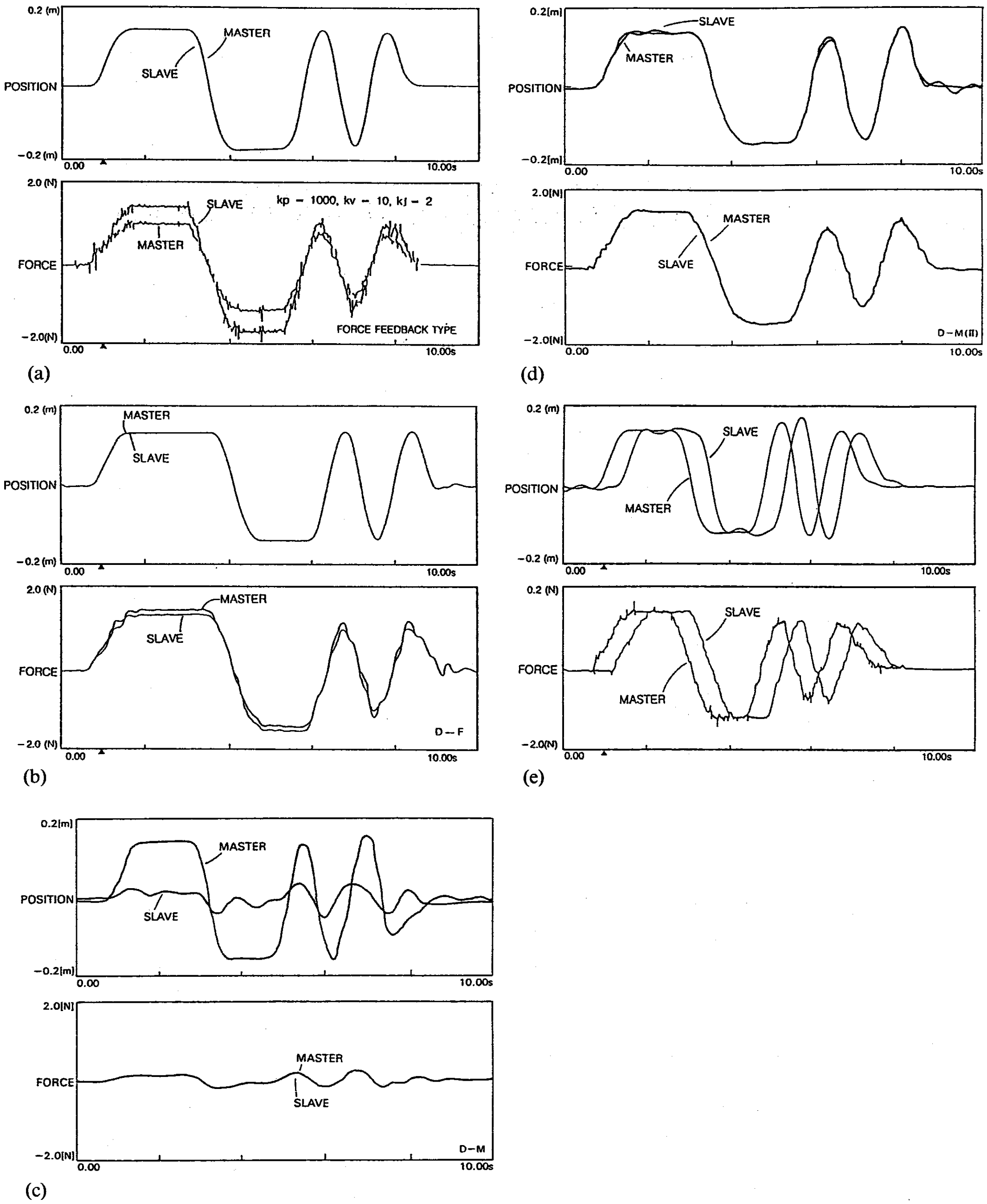


Figure 6. Simulation of force feedback type and impedance controlled MSMS. (a) Results of the conventional force feedback scheme; (b) results of the D-F type impedance controlled MSMS; (c) dual motion transmission method without the object model; (d) dual motion transmission method with the object model; (e) results for the system with a time delay of 0.5 s.

where K_f, K_v, and K_p are the force, velocity, and position feedback gains, respectively. In this system, the reflection force which the operator felt is (for simplicity, $M_m = M_s = M_0$, $B_m = B_s = K_0$)

$$F_0 = (1 + K_f)^{-1}(M_0\ddot{X} + B_0\dot{X}) + (1 + K_f)^{-1}K_f F_e. \tag{A6}$$

If the force feedback gain K_f is sufficiently large, then we get $F_0 = F_e$ approximately. However, since it makes the other gains K_p and K_v larger, instability may occur.

(2) Force reflection type

For the force reflection type MSMS, the master arm dynamics are described as

$$F_0 = M_m\ddot{X}_m + B_m\dot{X}_m + F_e. \tag{A7}$$

Also, the slave arm dynamics, its control scheme, and the object dynamics are

$$F_2 = M_s\ddot{X}_s + B_s\dot{X}_s + F_e, \tag{A8}$$

$$F_2 = K_v(\dot{X}_m - \dot{X}_s) + K_p(X_m - X_s), \tag{A9}$$

$$F_e = M\ddot{X}_s + B\dot{X}_s + K\,\delta X_s. \tag{A10}$$

In this system, the reflection force which the operator feels is (for simplicity, $M_m = M_s = M_0$, $B_m = B_s = B_0$)

$$F_0 = (M_0\ddot{X} + B_0\dot{X}) + F_e, \tag{A11}$$

where the dynamics of the slave arm are cancelled by the scheme. However, since the dynamics of the master arm are added to the reflection force, the force response becomes worst than that of the force feedback scheme.

(3) Symmetric type

For the force reflection type MSMS, the master arm dynamics and its control scheme are described as

$$F_0 = M_m\ddot{X}_m + B_m\dot{X}_m + F_1. \tag{A12}$$

$$F_1 = K_v(\dot{X}_m - \dot{X}_s) + K_p(X_m - X_s). \tag{A13}$$

Also, the slave arm dynamics, its control scheme, and the object dynamics are

$$F_2 = M_s\ddot{X}_s + B_s\dot{X}_s + F_e, \tag{A14}$$

$$F_2 = K_v(\dot{X}_m - \dot{X}_s) + K_p(X_m - X_s), \tag{A15}$$

$$F_e = M\ddot{X}_s + B\dot{X}_s + K\,\delta X_s, \tag{A16}$$

where it is assumed that the dynamics and the feedback gains of the master and slave arms are equal for simplicity. In this system, the reflection force which the operator feels is

$$F_0 = \{M_0(\ddot{X}_m + \ddot{X}_s) + B_0(\dot{X}_m + \dot{X}_s)\} + F_e \tag{A17}$$

Since the dynamics of both arms are added to the reflection force, the force response becomes worse than that of the force reflection scheme.

APPENDIX B. CONTROL SYSTEM OF THE MSMS INCLUDING THE OPERATOR'S DYNAMICS

Assume that the operator dynamics are

$$F_{op} - F_0 = M_{op}\ddot{X}_m + B_{op}\dot{X}_m + K_{op}X_m, \tag{B1}$$

where F_{op} indicates the kinaesthetic force; and M_{op}, B_{op}, and K_{op} represent the inertia, viscosity and stiffness matrices of the end-point of the operator arm. From Section 2.2, considering the D-F type MSMS, the following relationships are given from equations (B1) and (1)–(7):

$$F_{op} = (M_{op} + M_0 + M)\ddot{X} + (B_{op} + B_0 + B)\dot{X} + (K_{op} + K_0 + K)X, \tag{B2}$$

$$M_0\ddot{e} + B_0\dot{e} + K_0 e = 0. \tag{B3}$$

Since equation (B3) is equivalent to equation (8), the system including the operator dynamics remains stable. Equation (B2) also indicates the relationship between F_{op} and its object (the whole dynamics of his/her arm, the manipulator, and the object) where the dynamics of the operator M_{op}, B_{op}, and K_{op} are variable according to the kinaesthetic state of his/her arm.

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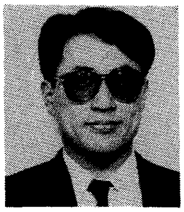

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