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Paper

Impedance-controlled master–slave manipulation system. Part II. Modification of force sensation and extension of operational capability

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Abstract—This research is concerned with tele-manipulation. A new master slave manipulation system has been presented in part I as the basis of an impedance-controlled master–slave manipulator for a tele-existence manipulation system. In Part II, the system is expanded so that it controls impedance models of both the environment and the manipulators, and modifies the force sensation to an operator as if he or she were in a different physical environment. Each manipulator impedance is determined using similarity transformation in physical modelling when the manipulators have different scales, force, and/or motion velocity conditions. The feasibility of the proposed method is demonstrated by experiments using a hardware direct-drive master manipulator and a software slave manipulator.

1. INTRODUCTION

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 aims at the natural and efficient remote control of robots by providing a human operator with a real-time sensation of presence that enables him or her to perform remote manipulation tasks dexterously with the feeling that they exist inside the slave robot in the remote environment. In tele-existence, natural feedback methods of not only visual information but also kinesthetic information, with which the operator is able to feel the robot arms as his or her own, are required. We have developed a master–slave manipulation system (MSMS) to establish kinesthetic feedback.

Symmetry type, force reflection type, and force feedback type MSMSs are used in conventional tele-operators. In those types, the dynamics of the master–slave arms are fixed [2]. Recently, the regulation of the arm dynamics of a MSMS has been shown to be effective, and several bilateral manipulation methods have been studied. Impedance matching type bilateral manipulation was proposed by Fukuda [3]. A virtual-model-following-control type MSMS was implemented by Furuta and Kosuge [4]. Yoshikawa and Yokokoji [5–7] and Dudragne *et al.* [8] proposed an intervened impedance type. Furthermore, a model reference control type has been presented by Fujii *et al.* [9] and Hanaford [10].

However, since the arm dynamics are fixed to some regulated values in these MSMS methods, there are no mechanisms to change the dynamics of the arm as required by the task and the operating environment. Also, the previous methods cannot be extended to a system in which the variable dynamics of MSMSs are utilized to assist the operational capability. It is necessary for tele-existence MSMSs to choose and design with known dynamics. A flexible MSMS is required to adapt to various kinds of tasks and environments. Also, since the previous MSMSs need 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. We have already proposed an impedance-controlled master–slave manipulation method to solve these problems [2].

The new MSMS combines the dynamics of each manipulator's end-point, and regulates them finely so that an operator can feel direct manipulation of an object. However, the MSMS cannot be adapted to all the task or environment conditions, or to a particular operational capability for the following reasons. First, tele-existence manipulation requires not only the direct reflection of the sensation of the slave arm to an operator, but also modification of the sensation to assist him or her. For instance, when the inertia or viscosity of an object is too large for it to be manipulated easily, the object's apparent impedance should be reduced. Tachi and Sakaki proposed a bilateral control method in which the environment dynamics are represented as impedance and the impedances of both an arm and its environment are controlled simultaneously [2]. A more extended MSMS using such a bilateral method is required to regulate the sensation of manipulation and to present various kinds of sensation of presence. Second, tele-existence should be implemented not only in the conventional case where the manipulators are controlled with the same scale, motion velocity, and input/output force conditions, but also in the case where the physical conditions of scales, motion velocity, and input/output forces are different from each other. Arai has proposed a different construction of an MSMS, considering the master operation and the slave task capability [11]. However, the system does not deal with an MSMS in different physical conditions. Fukuda has presented a generalized method of impedance model representation of a micro-manipulator system which is operated under different scale and input/output force conditions [3]. Tachi *et al.* have proposed an impedance-controlled MSMS to adapt the model to such conditions [2]. However, their methods do not show the systematic design for construction of an MSMS.

This paper aims at an extension of the impedance-controlled MSMS, and a system design to provide the modification of force sensation and sensation in different physical conditions.

The paper is organized as follows. In Section 2, the principle of the impedance-controlled MSMS is explained, and the problems of the MSMS in different physical conditions and the necessity for the extension of the MSMS are also shown. In Section 3, the system design of the extended MSMS is explained. In Section 4, the experimental results are given. The conclusions of the paper are presented in Section 5.

2. FUNDAMENTAL AND EXTENDED SYSTEMS OF IMPEDANCE-CONTROLLED MSMS

In this section, the principle of the fundamental impedance-controlled MSMS is explained in physical equivalence conditions. The problems of the MSMS in different physical conditions and the necessity for the extension of the MSMS are also shown.

2.1. Fundamental system 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 MSMS in which impedance control is the fundamental part of the MSMS.

Impedance control deals with the dynamic interaction between a robot and its environment. The manipulator can execute stable force control in contact with an object by the control method [12, 13]. When performing a contact task, the relationship between the robot and its environment is defined as mechanical impedance; their dynamic interaction is considered as a change in the impedance. The fundamental concept of the control shows the integrated control scheme of the robot dynamics plus environment dynamics. Therefore, it is also effective for the MSMS dealt with in this paper [2, 14].

Figure 1 shows the systematic concept of the fundamental impedance-controlled MSMS. The environment where a slave manipulator executes its task is called the task environment, which includes the task objects. The environment model which the master system creates in the master side is called the operation environment. The MSMS is composed of two parts: a master and a slave system. Each manipulator is controlled by its system computer. The computer is composed of the supervisor, which supervises the arm control, and the environment simulator, which creates its environment model. Also, the master and slave systems transmit information on the motion and force of the manipulators to each other.

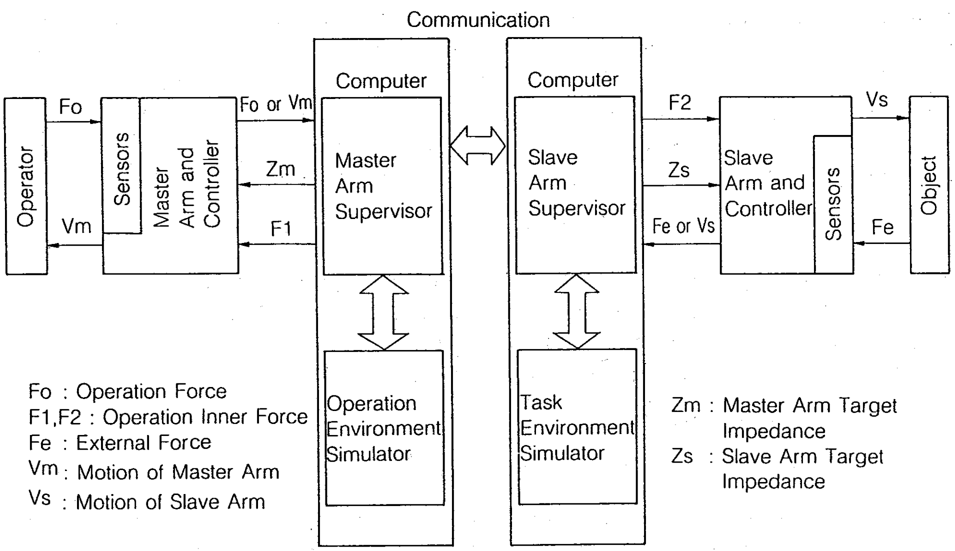


Figure 1. Basic concept of the impedance-controlled MSMS.

The fundamental MSMS which has been proposed for conditions of physical equivalence and no time delay can be classified into four basic types according to the types of information exchanged between the master and slave [2]. For simplicity, the dual force transmission method (D-F) is explained here as one of the MSMS implementations.

In the D-F type, 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 with force/torque sensors (see Fig. 1).

Assume that the master and slave arms have the same dynamics or the dynamics are apparently coincident by the impedance control command of the supervisor [14, 15]. The equation of motion of the master manipulator and the master–slave control strategy can be described as follows:

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

$$F_1 = -F_e. \tag{2}$$

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

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

$$F_2 = F_0. \tag{4}$$

Also, the equation of motion of an object is described as follows:

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

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, F_2 is that of the slave manipulator, and F_e is 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. 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. By use of the scheme, from equations (1)–(5), the positional error $e = X_m - X_s$ can be represented by

$$M_0\ddot{e} + B_0\dot{e} + K_0e = 0. \tag{6}$$

The error e can be reduced to zero by selecting appropriately 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

$$\begin{aligned} F_0 &= (M_0\ddot{X} + B_0\dot{X} + K_0X) + F_e \\ &= (M_0\ddot{X} + B_0\dot{X} + K_0X) + (M\ddot{X} + B\dot{X} + K\,\delta X). \end{aligned} \tag{7}$$

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.

2.2. *Necessity for the extended system*

This paper aims at not only the ideal tele-operation of the direct manipulation of an object, but also the extension of the operational capability to create an ideal operation environment. Since an ideal operation environment depends on the operation task, the task environment, and the capability of the operator, the general definition of the operation environment is a topic for the future. However, the proposed MSMS in which the impedance model representation of the dynamics of both the manipulators and their environments, and the strategy to control each manipulator's dynamics directly and independently are implemented may be a first step. In this section, the modification of force sensation and the adaptation to different physical conditions are discussed.

The first issue is the modification of force sensation. In a real system, the slave task environment is not always an easy environment for an operator. Some dynamics of a task environment may disturb the operator, or require some other useful dynamics for better task execution. For instance, one difficult case is where a large inertia object is required to be moved, or a task must be performed in different viscosity regions. Another case is where an operator cannot detect the borders of regions when the task would be helped by the detection of the different viscosities of the regions. Although, from the viewpoint of fundamental tele-existence, the first aim is to detect the real environment, the virtual modification of the environment dynamics, including the object, in order to help the operator is also important. In the latter cases, the task may become easier when the object inertia is virtually reduced, or when the difference in viscosity of the regions is made larger. Since the operator executes the task with the arm impedance, the impedance should be modified along the arm motion for the virtual modification of the environment dynamics.

The second issue is the adaptation to different physical conditions. In general, the motion velocity or input/output force of a slave manipulator is different from that of a human arm, which is dependent on the task environment. For instance, there are many different slave manipulators, such as a micro-manipulator for which scale and force are small, a large-scale and high-force capability manipulator, and a long-scale and low-velocity motion space manipulator. In conventional strategies, since these manipulators are dealt with only in geometrical similarity, an operator operates the master arm with the geometrically transformed force/motion information in geometrical similarity. However, it is not sufficient for the real operation of the direct manipulation of the environment with the desired motion velocity to operate the arm with geometrical similarity. Physical similarity is required for the extended MSMS operation where the master and slave arms and their environments are considered as physical phenomena [13].

This means that since MSMSs operated only following the operator's motion cannot increase the operator's capability, it requires him or her to have some operational training. In addition, the master arm operation along the desired motion velocity of the slave arm disturbs the operator in some cases. For instance, those cases where the slave arm is required to move at a velocity at which one cannot move because it is too high or too low. The desired specification of an MSMS even in those cases is that the operator operates the master arm at his or her normal motion velocity, while the slave arm executes its task at the desired motion velocity, which is transformed from the operator motion by some mapping. Machida *et al.* [16] considered a space arm at low motion velocity, and proposed the transform mapping of the operator motion to the low arm motion by some task rearrangements, like a videotape. However, since the transformation deals with the time history of the arm motion, the similarity does not satisfy the physical generality.

Another issue is that the transformation of input/output forces may provide high operational capability. For instance, the force sensation from working with a blood vessel with a micro-manipulator, changed virtually to the force sensation of rubber tubes helps the operation. A sensation changed not only by geometrical similarity but also by physical similarity, including the object material specification, gives a good operation capability sensation.

The proposed MSMS in this paper transforms the master–slave arm motions not only by time history or geometrical similarity, but also by physical similarity, i.e. physical modelling rules, and regulates the arm impedances in the case of different scales, input/output forces, and motions by rules for providing real sensation of presence with physical generality.

The whole system structure of the extended impedance-controlled MSMS including time lag is shown in Fig. 2. The conventional bilateral systems are generalized to the fundamental impedance-controlled MSMS for the real and direct manipulation sensation of an object. In the fundamental system, both arms are similar in physical meaning, and no modification of the environment dynamics and

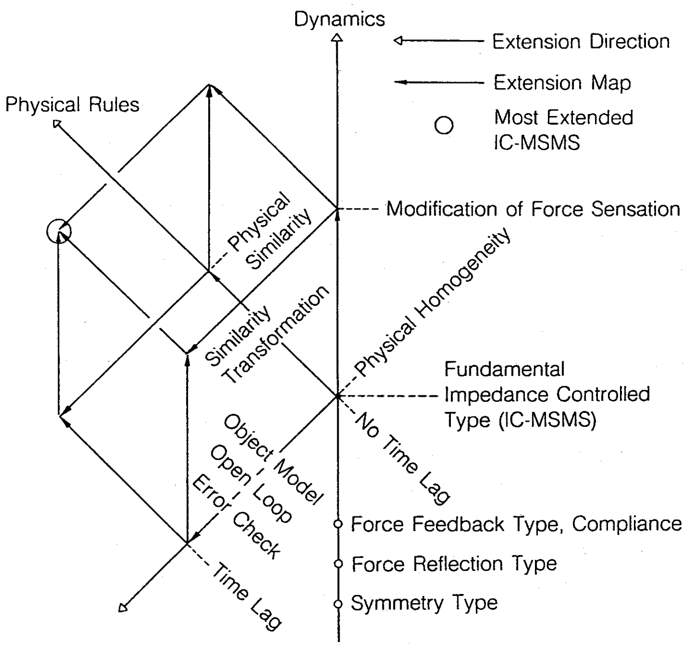


Figure 2. Extension graph of bilateral MSMS.

time delay are considered. From this point, the system is extended in three directions: dynamics, physical rules, and time delay. Force sensation modification, transformation of motion velocity and input/output forces, and object modelling are applied in the dynamics, physical rules, and time delay directions, respectively. The furthest extension point is indicated by the circle in the figure.

3. EXTENDED IMPEDANCE-CONTROLLED MSMS

In this section the construction of the extended MSMS with respect to two specifications (motion and velocity), shown in Section 2, is explained.

3.1. Task environment model

As a first step, the MSMS assesses the object dynamics automatically or by operator command. The assessment is made using the arm dynamics already identified and the motion of the object when manipulated by the arm [2]. Secondly, the operation environment model of the master system is constructed together with the slave task environment model [2]. 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:

$$Z(X) = [z_{p1}, z_{p2}, z_{p3}, z_{r1}, z_{r2}, z_{r3}]^{T}. \tag{8}$$

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

$$\Gamma(\cdot) = \mathrm{SCL}(\mathrm{ROT}(\mathrm{TRNS}(\cdot))). \tag{9}$$

Define the coincidence of the task environment and operation environment as follows:

$$Z_t(X_t) = Z_0(X_0), \tag{10}$$

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

$$X_0 = \Gamma(X_t). \tag{11}$$

3.2. Modification of force sensation

The method for modifying the force sensation using an operation environment model is explained as follows.

3.2.1. Recording and replay of the environment impedance. The impedance of the environment is recorded and repeated by operator command.

After the environment dynamics assessment with the slave arm is finished, the impedance data are recorded in the computer. Since the environment impedance is defined at the contact point by the slave arm, the position is also recorded with the data. Then the environment impedance data are transmitted to the master system, which is explained in Section 3.1, and the environment model is constructed in the master system. After the modelling, when the operator moves the master arm he or she can feel the environment model dynamics (inertia, viscosity, and stiffness) by the feedback of the impedance data of the arm position. Therefore, the identified environment reappears in front of the operator.

For instance, consider the following environment: a stiff wall on the left side of the slave arm, a rubber film on the right side, and water below the arm. The dynamics of each part of the environment is assessed, and the environment model is constructed with the data. When the operator moves the master arm, he or she can feel the stiff wall, the rubber film, and the water by the feedback of the high stiffness, elasticity, and viscosity on the left side, the right side, and below the arm, respectively.

In this way, the recorded environment impedance is not only simulated, but it also helps with repetitive training for operation, especially in the case of complicated and dangerous tasks. This means that the operator repeats the training only with the master system, and sets the optimal operation and its target impedance. The data are transmitted to the slave system and operate the slave arm. In another case, checks for dangerous loads or disturbances are also available, as described below.

3.2.2. Regulation of the environment. In this section, the regulation of the environment in each system is explained.

In the case of the coincidence of both environment impedance models, the models are not always sufficient for operational capability. This means that the models should be regulated to be some well-specified impedance in this case, as follows.

(1) Define the given and ideal operation environment impedances as $Z_0(X_0)$ and $Z_{01}(X_0)$, respectively. Then consider the following mapping:

$$Z_{02}(X_0) = \Psi(Z_0(X_0)). \tag{12}$$

The mapping Ψ indicates some transformation of the given impedance model $Z_0(X_0)$ to the virtual impedance model $Z_{02}(X_0)$ included in the ideal operation-environment impedance region. For instance, the mapping Ψ regulates the parts of $Z_0(X_0)$ of which the upper/lower limit values may cause instability to the upper/lower limit values $Z_{01u}(X_0)$ and $Z_{01l}(X_0)$ of the ideal region, and continues those values with their neighbourhood. By this regulation, the transformed impedance $Z_{02}(X_0)$ satisfies the following condition about parameter $p(\cdot)$:

$$p(Z_{01l}(X_0)) \leqslant p(Z_{02}(X_0)) \leqslant p(Z_{01u}(X_0)). \tag{13}$$

The regulated impedance $Z_{02}(X_0)$ is included in the ideal operation environment impedance region.

(2) By the mapping Ψ, the ideal operation environment is approximately constructed. However, since the model is to be considered for general operators, more modification of the model is required to adapt it to the individual operator

or task. Therefore, the model $Z_{02}(X_0)$ is modified to the ideal model $Z_{03}(X_0)$ by operator commands.

(3) Based on the environment model, the task environment model is created in the slave system by the inverse mapping of Γ defined in Section 3.1.2. Then both models are coincident.

In this way, the regulation of the environment impedance is the transformation of the operation environment model to the good operational capability model in physical equivalence. This means that most of the operation environment model impedance $Z_0(X_0)$ is included in the ideal model region, and the part of the given model which is out of the region is modified by the mapping Ψ. However, it is the case where the operation environment model is very different from the ideal one (for instance, the scale or motion velocities of both arms are different) which needs another transformation. This case is discussed in Section 3.3.

3.2.3. Modification of the force sensation. In this section, the regulation or modification of the force sensation is discussed.

The manipulator dynamics are given as follows:

$$I\ddot{\Theta} + D_v\dot{\Theta} = T_a + J^T F_e, \tag{14}$$

where I, D_v, T_a, J^T, and Θ indicated the inertia, viscosity matrices, output torque vector, transposed Jacobian matrix, and angular vector, respectively.

Define the whole system target impedance as $Z(s)$, when the manipulator contacts its object,

$$Z(s) = M_{d1}s + B_{d1} + (1/s)K_{d1}. \tag{15}$$

The equation of the apparent whole system dynamics is

$$F_e = M_{d1}\ddot{X} + B_{d1}\dot{X} + K_{d1}(X - X_0). \tag{16}$$

Then the output torque is calculated to realize the target impedance (M_{d1}, B_{d1}, K_{d1}) in (15) as follows, when the manipulator contacts the objects with the impedance (M_{obj}, B_{obj}, K_{obj}),

$$\begin{aligned} T_a = {} & (I + J^T M_{obj} J - J^T M_{d1} J)\ddot{\Theta} \\ & + (D_v + J^T B_{obj} J + J^T M_{obj} \dot{J} - J^T M_{d1} \dot{J} - J^T B_{d1} J)\dot{\Theta} \\ & + J^T\{K_{obj}(L(\Theta) - X_e) + K_d(X_0 - L(\Theta))\}. \end{aligned} \tag{17}$$

A block diagram of the system is given in Fig. 3.

Consider the case where the slave manipulator pushes or handles its object to move it in manufacturing tasks. The task with such movable objects is discussed below.

(1) The environment model is changed immediately by the calculation of the combined impedances of both the arm and its object in the case of continuous manipulation without release of the object. Since the handled object can be considered as part of the arm, their future motion is estimated, and their impedance is controlled by the whole system target impedance.

As discussed in Section 3.1, the object impedance (M_{obj1}, B_{obj1}, K_{obj1}) is also calculated from the slave arm and whole system target impedances (M_d, B_d, K_d)

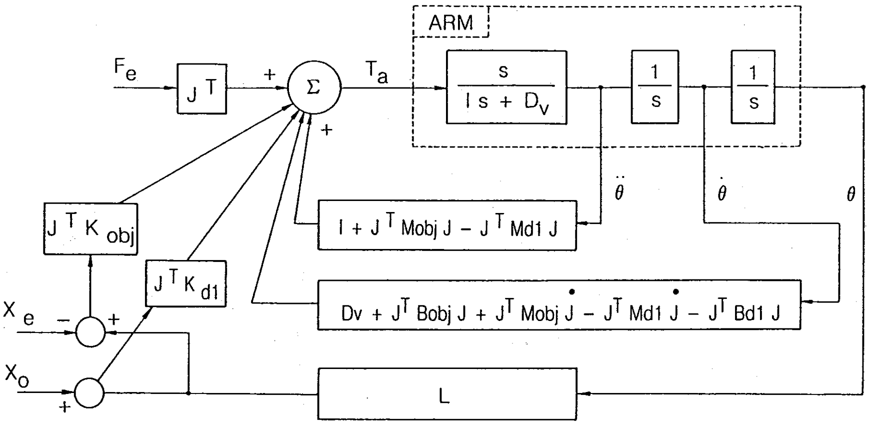


Figure 3. Block diagram of impedance control with an object.

and (M_s, B_s, K_s) [2]:

$$K_{\text{obj1}} = (K_s^{-1} - K_d^{-1})^{-1} \quad (18)$$

$$B_{\text{obj1}} = (B_s^{-1} - B_d^{-1})^{-1} \quad (19)$$

$$M_{\text{obj1}} = (M_s^{-1} - M_d^{-1})^{-1}. \quad (20)$$

Define these parameters (M_{obj1}, B_{obj1}, K_{obj1}) as (M_{obj}, B_{obj}, K_{obj}) again, and substituting them in equation (17), the target impedance control becomes available.

(2) Consider the case where the slave manipulator releases its object, for instance when the arm pushes it. When the arm contacts its object, the combined impedance is calculated. After the release, the future motion of the object is estimated by the velocity information when the arm released it together with information on the object and its neighbourhood environment impedances. The environment model is change immediately from the estimated effort.

In this way, the operator is able to get his or her good operational capability environment by regulation of the identified environment model so as to control it as if it were part of his or her body. The regulation is executed by considering the whole impedance of the manipulator and its environment in contact with the arm, and controlling the environment dynamics by including feedback of the impedance to the arm control.

3.3. Extension of operational capability by applying a physical similarity transformation

Considering the environment as an impedance model, both the operation and task environment models are required to satisfy not only a geometrical relationship, but also a relationship of physical similarity. In this section, it is shown, first, that the physical similarity of both arms is sufficient if both arm target impedances are coincident in the fundamental impedance controlled MSMS explained in Section 2. Secondly, we discuss the extension of the MSMS for operational capability in terms of motion velocity and input/output force conditions by applying the relationship of the physical similarity of both environments.

(1) In order that the same physical phenomena occur in both environments, physical similarity rules must be such that the physical rules are the same in both environments and all the physical parameters are similar to each other [13]. When both arm impedances in the MSMS are coincident, the following theorem is valid.

Theorem 1. If the impedances of the operation and task environments coincide, physical similarity is satisfied naturally. This means that the following relationship holds. Assume that the dominating physical rules are the following three rules, which are described by representative quantities [13]:

$$\text{Rule of inertia: } f_i = f\alpha = \rho l^4/t^2, \tag{21}$$

$$\text{Relationship of viscosity: } f_v = bv = \mu l v = \mu l^2/t, \tag{22}$$

$$\text{Relationship of stiffness: } f_k = kl, \tag{23}$$

where ρ, l, μ, and t indicate the representative quantities of density, scale, viscosity, and time, respectively [14]. Representing them by π-numbers,

$$\pi_1 = f_i/f_v = \rho l^2/(\mu t), \tag{24}$$

$$\pi_2 = f_k/f_v = kt/(\mu l), \tag{25}$$

slave system parameters are described by adding a prime to the master parameters.

When both impedances of the MSMS are equal, i.e.

$$m = m', \quad b = b', \quad k = k', \tag{26}$$

the following relationships are valid (see the Appendix for their proof),

$$\pi_1 = \pi_1', \quad \pi_2 = \pi_2'. \tag{27}$$

(2) Consider the extension of the operational capability by transforming the task motion velocity. When it is difficult to execute tasks at the desired motion velocity, the MSMS is extended by simulating and recording the target task motion only in the master system, transforming the recorded motion velocity to the desired motion velocity by physical similarity rules, transmitting the data to the slave system, and executing the task at the desired motion velocity. The operation task velocity in the master system is decided by transformation of each impedance parameter with the motion velocity ratio of each environment.

Theorem 2. When the geometrical similarity ratio l^* of the operation and task environments is given, physical similarity is satisfied by some suitable transformation of the impedance parameter ratio for the motion velocity ratio v^*. Assuming that the dominating physical rules are the same as those for Theorem 1, setting the geometrical similarity ratio l^*, the density ratio ρ^*, and the motion velocity ratio v^*, physical similarity rules are satisfied for the MSMS by deciding the following impedance parameters (see the Appendix for proof):

$$\begin{aligned} m/m' &= \rho^* l^{*3}, \\ b/b' &= \rho^* l^{*2} v^*, \\ k/k' &= \rho^* l^* v^{*2}. \end{aligned} \tag{28}$$

where $l^* = l/l'$, $\rho^* = \rho/\rho'$, $v^* = v/v'$.

The transformation of motion velocity is regarded as the transformation of the master operation torque to the slave inner torque. The following corollary applies.

Corollary 2.1. In an MSMS which satisfies the physical rule of the motion velocity (Theorem 2), if $\rho^* = 1$, $l^* = 1$, and the motion velocity ratio v^* is given, the time history of the master operation force $f_m(t)$ and the time history of the slave inner force $f_s(t)$ are represented by the following relationship (see the Appendix for proof):

$$f_s(t) = (1/v^{*2}) f_m(t/v^*). \tag{29}$$

Note that the corollary can be extended easily for general ρ and l^*.

(3) The real force sensation of presence is given by transformation of the input/output force condition considering not only the geometrical ratio, but also the physical similarity of both environments including the object material specification.

Theorem 3. When the geometrical similarity ratio l^* of the operation and task environments is given, an impedance parameter ratio to decide a suitable ratio for each physical specification (density, viscosity, stiffness) of each environment exists, and satisfies the physical similarity rules. The input/output force condition ratio in the MSMS is given by the geometrical ratio and the impedance parameter ratios. Concretely, if the dominating physical rules are the same as those in Theorem 1, the geometrical similarity ratio l^* is given, and either the density ratio ρ^*, the viscosity ratio μ^*, or the stiffness ratio k^* is given, then the impedance parameter ratio is decided, for instance, by the density ratio ρ^* as follows:

$$m/m' = b/b' = k/k' = \rho^* l^{*3}, \tag{30}$$

and the relationship satisfies physical similarity rules. In this case, the input/output force condition is

$$f/f' = \rho^* l^{*4}, \tag{31}$$

where

$$l^* = l/l', \quad \rho^* = \rho/\rho', \quad \mu^* = \mu/\mu', \quad k^* = k/k' \tag{32}$$

(see the Appendix for proof).

The proposed MSMS provides an operator with the real sensation of presence with physical generality by regulation of the impedance parameters which satisfy physical similarity rules in the case of different scales, different input/output forces, or different motion velocity conditions. In addition, the stability of the MSMS applied with a similarity transformation is preserved (see the Appendix for proof).

3.4. *Control flow of an extended impedance-controlled MSMS*

In this section, the operational flow of the extended impedance controlled MSMS is discussed. Figure 4 shows the operation algorithm.

(1) As discussed in Section 3.1, the slave system assesses its environment by the

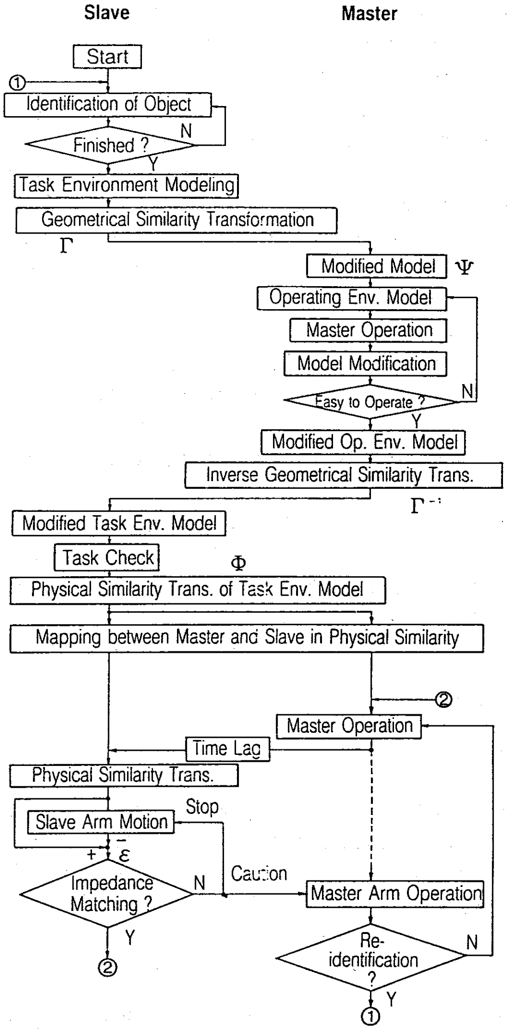


Figure 4. Operation flow of the impedance-controlled MSMS.

results of the slave arm motion, the task environment modelling, and the transmission of position and impedance data of the environment to the master system, which creates the operation environment model with the data coincident with the slave one [2].

(2) Secondly, the master system regulates the operation environment model. If the master scale, input/output force, and motion velocity conditions for good operational capability are different from the desired ones in the slave system, the MSMS regulates each impedance parameter to satisfy the physical similarity rules. The regulation causes the transformation of the geometrical, input/output force, and motion velocity conditions (see Sections 3.2.2 and 3.3).

(3) The operator operates only the master system to contact the operation environment with the master arm. The operator gives commands to modify the

environment model for good operational capability. The result of the modification is transmitted to the slave system, and the slave environment is changed to coincide with the data (see Sections 3.2.1 and 3.2.2).

(4) Both systems work, and the operator executes tasks. The master system supervisor calculates the reflection force with the master arm motion data substituted into the master arm equation of motion based on the operation environment model (target impedance), and commands the desired output torque to the arm controller. The master arm motion data are transmitted to the slave system simultaneously. On the other hand, the slave system supervisor calculates the desired output torque from the motion data and relays it to the slave arm controller (see Section 3.2.3).

In the MSMS a task with a time delay, and teaching of the slave arm motion by repeating the task exercise simulated in the master system discussed in Section 3.2.1 can both be done. In addition, as shown in Section 3.3, the transformation of the slave arm input/output forces and motion velocity conditions from the master ones is also possible (mapping Φ in Fig. 4).

(5) The real motion of the slave arm observed by the slave system is compared with that of the simulation model. If there is an error between them, the slave system sends a caution command to the master system, executes a reidentification routine and modifies the task environment model [2].

4. CONTROL EXPERIMENTS

4.1. Experimental hardware

A direct-drive manipulator with three degrees of freedom, a precise mathematical model of which had been acquired, was used as a master manipulator [12]. Each joint of the manipulator was driven by a direct-drive (DD) DC motor (Inland) [17]. Figure 5 shows the experimental system.

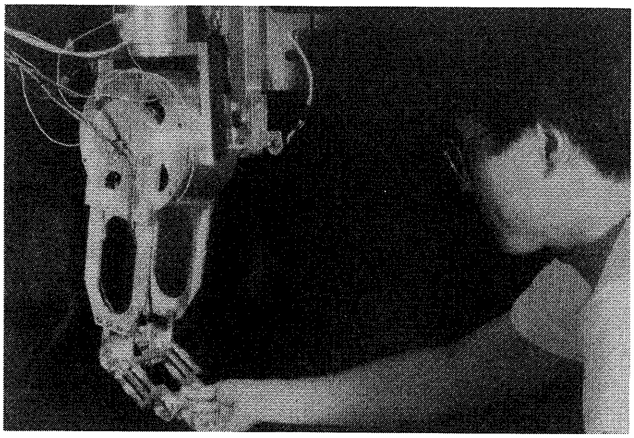
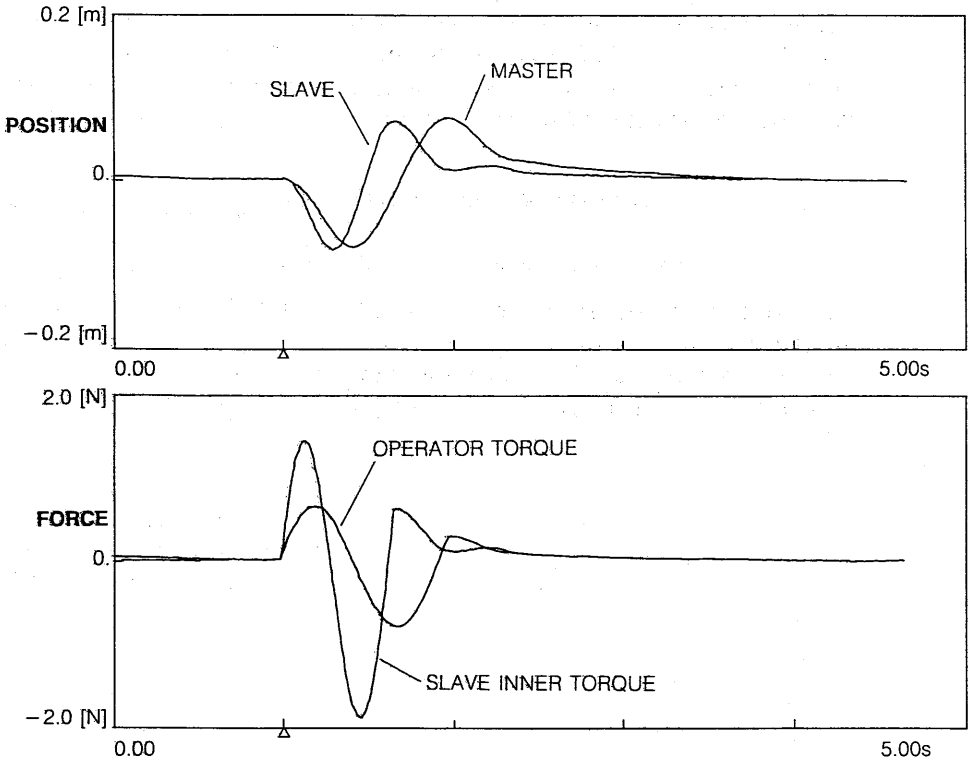


Figure 5. Experimental system.

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

4.2. Application of physical similarity transformation (task velocity transformation experiment)

The transformation of the master slave arm motion velocities by Theorem 2 and Corollary 2.1 was tested as follows. If $\rho^* = 1$, $l^* = 1$, and the motion velocity ratio



Transformation which maintains Physical Similarity
Note : Transformed Slave Motion is Simulated offline.
$(\rho^* = 1,\ l^* = 1,\ V^* = 2/3)$
Master Impedance Parameters :
$M_0 = 0.5$ [kg], $B_0 = 20.0$ [N/(m/s)], $K_0 = 40.0$ [N/m]
Slave Impedance Parameters;
$M_s = 0.5$ [kg], $B_s = 30.0$ [N/(m/s)], $K_s = 90.0$ [N/m]

Figure 6. Simulation results of velocity transformation which maintains physical similarity.

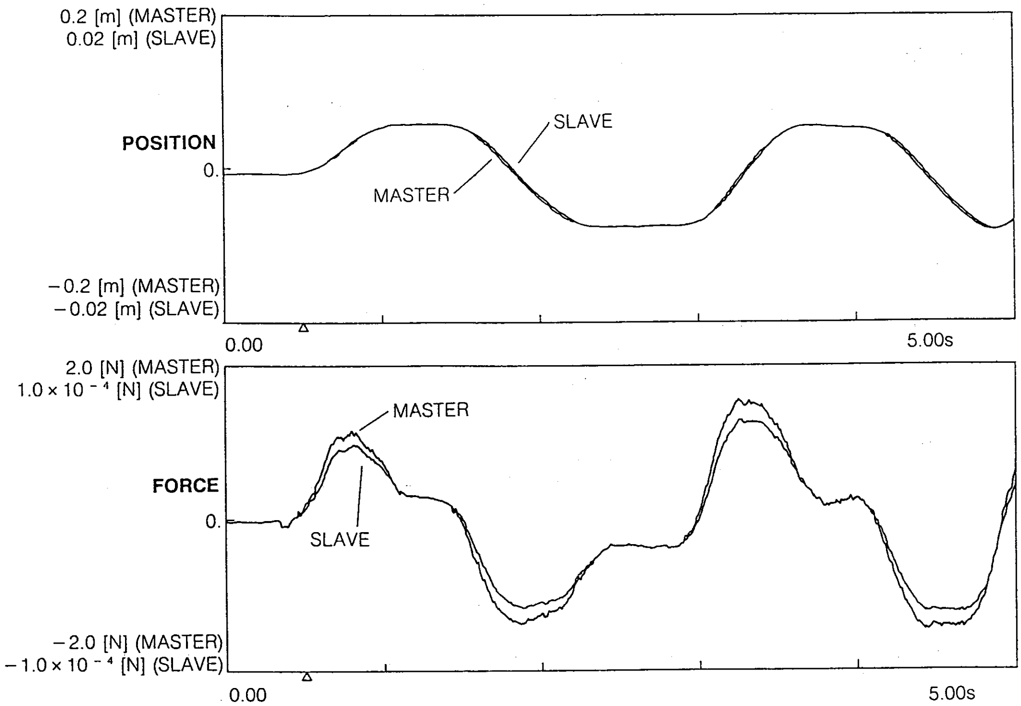
$v^* = 2/3$, by Corollary 2.1 each impedance parameter of the MSMS is given as

$$M_0 = 0.5 \text{ kg}, \quad B_0 = 20.0 \text{ N/(m/s)}, \quad K_0 = 40.0 \text{ N/m},$$
$$M_s = 0.5 \text{ kg}, \quad B_s = 30.0 \text{ N/(m/s)}, \quad K_s = 90.0 \text{ N/m}.$$

For each arm with these parameters the master operation force and the transformed force appearing as the slave inner torque were given. Figure 6 shows the time history of the master operation force and its position, and the slave inner torque and its position. DD arms were used for the MSMS arms. The slave arm executed motion compressed to $v^* = 2/3$ of the master one while maintaining physical similarity by the transformed target impedance and inner torque of the slave arm.

4.3. Application of physical similarity transformation (input/output force condition transformation experiment)

The input/output force condition transformation was tested by using Theorem 3. The conditions $\rho^* = 2$ and $l^* = 10$ are given, and the impedance parameters of a



Note: $\rho^* = 2$, $l^* = 10$
Master Impedance Parameters ;
$M_0 = 0.05$ [kg], $B_0 = 1.0$ [N/(m/s)], $K_0 = 0.1$ [N/m]
Object Impedance Parameters in Master System ;
$M = 0.01$ [kg], $B = 5.0$ [N/(m/s)], $K = 5.0$ [N/m]
Slave Impedance Parameters keep $1/\rho^* l^{*3} = 1/2000$ *times of Impedance Parameters in Master System.*

Figure 7. Simulation results of force transformation which maintains physical similarity.

master arm and its object model are given as follows. By Theorem 3, the slave system impedance parameters are $1/\rho^* l^{*3} = 1/2000$ times the master system ones.

$$M_0 = 0.05 \text{ kg}, \quad B_0 = 1.0 \text{ N/(m/s)}, \quad K_0 = 0.1 \text{ N/m},$$
$$M = 0.01 \text{ kg}, \quad B = 5.0 \text{ N/(m/s)}, \quad K = 5.0 \text{ N/m}.$$

Using the dual force transmission method, the DD arm was controlled as the master arm, and a slave arm was simulated in software. Figure 7 shows the time histories of the position and force of both arms. The slave arm was controlled to a position of $1/l^* = 1/10$ times the master one, and the force of $\rho^* l^{*4} = 2000$ times the slave one was reflected to the operator, as shown by Theorem 3.

6. CONCLUSION

This paper presents a MSMS with a real sensation of presence for tele-existence. In this system, an impedance control method is applied as the basic control scheme. We have extended the fundamental part of the MSMS to identify and regulate the environment to provide optimization and support according to the operator task. The concept of the proposed MSMS is to represent the arm and its environment dynamics as a mechanical impedance model, and to rearrange the model for operational capability in advanced tele-presence sensation. The system is called an impedance-controlled MSMS. The system was extended to solve the following issues.

The first issue is the modification of force sensation. The real identification of the task environment is the prior issue in tele-existence. In addition, the apparent environment impedance model including the object is modified according to the operator's capability, which provides good force sensation of presence.

The second issue is the adaptation to cases of different physical conditions. Considering both arm motions and their environments with a physical similarity relationship, i.e. physical similarity rules, each arm and environment impedance is regulated to satisfy the rules in cases of different scale, input/output force, or motion velocity conditions. This provides a real sensation of presence while maintaining physical generality.

The issues for the future are the identification of the non-linear dynamics environment and its control method, the control method of the active dynamics object, the analysis of the ideal dynamics environment for an operator, and the implementation of a database of the task environment impedance to predict the object motion released by the arm.

REFERENCES

1. S. Tachi, K. Komoriya and M. Kaneko, "Tele-existence (I)," in *Proc. RoManSy 84*, pp. 245–254, Udine, 1984
2. S. Tachi and T. Sakaki, "Impedance-controlled master–slave system. Part I. Basic concept and its application to a system with time delay," *J. Adv. Robotics*, (in press).
3. T. Fukuda, "Bilateral control of a micro manipulator," in *Proc. 25th SICE Conf.*, pp. 715–716, 1986 (in Japanese).
4. K. Furuta, K. Kosuge, Y. Shiote and H. Hatano, "Master–slave manipulator control using a virtual inner model," *J. Soc. Instrum. Control Eng.*, vol. 24, no. 2, pp. 176–182, 1988 (in Japanese).

5. T. Yoshikawa and Y. Yokokoji, "Manipulability and stability analysis of master–slave systems," in *Proc. 5th Robotics Soc. Jpn.*, pp. 109–112, 1987 (in Japanese).
6. T. Yoshikawa and Y. Yokokoji, "Dynamic control of master–slave manipulators," in *Proc. 27th SICE* pp. 375–376, 1988 (in Japanese).
7. T. Yoshikawa and Y. Yokokoji, "Dynamic control of master–slave manipulators to achieve some required impedance," in *Proc. 6th Robotics Soc. Jpn.*, pp. 406–410, 1988 (in Japanese).
8. J. Dudragne, C. Androit, R. Fournier and J. Vuillemey, "A generalized bilateral control applied to master–slave manipulators," *Proc. 20th ISIR*, pp. 435–442, 1989.
9. S. Fujii, R. Suematsu, Y. Hayakawa, T. Hayase and S. Kajiwara, "Adaptive control of master–slave systems," in *Proc. 6th Robotics Soc. Jpn.*, pp. 395–398, 1988 (in Japanese).
10. B. Hanaford, "A design framework for tele-operators with kinesthetic feedback," *IEEE Trans. Robot. Autom*, vol. 5, no. 4, pp. 426–434, 1989.
11. T. Arai, "Bilateral master–slave control of different configuration manipulators," *J. Robotics Soc. Jpn.*, vol. 4, no. 5, pp. 3–13, 1986 (in Japanese).
12. N. Hogan, "Stable execution of contact tasks using impedance control," *Proc. IEEE Int. Conf. Robot. Autom.*, vol. 2, pp. 1047–1054, 1987.
13. I. Emori, "Theory and application of model experiments," *Gihodo*, 1973 (in Japanese).
14. S. Tachi, T. Sakaki, H. Arai, S. Nishizawa and J. F. Pelaez-Polo, "Impedance control of a direct drive manipulator without using force sensors," *J. Robotics Soc. Jpn*, vol. 7, no. 3, pp. 175–187, 1989 (in Japanese).
15. N. Hogan, "Impedance control, parts I–III," *ASME Trans.*, vol. 107, pp. 1–24, 1985.
16. K. Machida, Y. Toda and T. Iwata, "Graphics-simulator-augmented teleoperation system for space applications," *J. Spacecraft and Rockets*, vol. 27, no. 1, pp. 64–69, 1990.
17. H. Asada, "Development of a direct drive robot and its control performance," *J. Soc. Instrum. Control Eng.*, vol. 19, no. 1, pp. 77–84, 1983 (in Japanese).

APPENDIX A. PROOFS OF PHYSICAL SIMILARITY RULES APPLICATION THEOREMS

Proof of Theorem 1

The condition to satisfy the physical similarity rules is

$$\pi_i = \pi_i', \quad i = 1, 2. \tag{A1}$$

That is,

$$\rho l^2/\mu t = \rho' l'^2/\mu' t', \tag{A2}$$

$$kt/\mu l = k' t'/\mu' l'. \tag{A3}$$

Since both impedances in MSMS coincide,

$$m = m', \quad b = b', \quad k = k', \tag{A4}$$

i.e.

$$\rho l^3 = \rho' l'^3, \quad \mu l = \mu' l', \quad k = k'. \tag{A5}$$

Since the MSMS is operated in real-time control.

$$t = t'. \tag{A6}$$

These conditions satisfy the physical similarity rules as follows:

$$\begin{aligned}\pi_1 &= \rho l^2/\mu t\\ &= (\rho l^3/\mu l)(1/t)\\ &= (\rho' l'^3/\mu' l')(1/t')\\ &= \rho' l'^2/\mu' t'\\ &= \pi_1',\end{aligned} \tag{A7}$$

$$\begin{aligned}\pi_2 &= kt/\mu l\\ &= (k/\mu l)t\\ &= (k'/\mu' l')t'\\ &= k't'/\mu' l'\\ &= \pi_2'.\end{aligned} \tag{A8}$$

Q.E.D.

Proof of Theorem 2

From Theorem 1, the conditions for physical similarity are

$$\rho l^2/\mu t = \rho' l'^2/\mu' t', \tag{A9}$$

$$kt/\mu l = k't'/\mu' l'. \tag{A10}$$

Therefore,

$$\rho^* l^{*2} = \mu t/\mu' t', \tag{A11}$$

$$l^* \mu/\mu' = kt/k't'. \tag{A12}$$

It is shown that they are valid. From the assumption of Theorem 2.

$$\begin{aligned}\mu l/\mu' l' &= \rho^* l^{*2}(v/v')\\ &= \rho^* l^{*3}(t/t').\end{aligned} \tag{A13}$$

Then

$$\mu t/\mu' t' = \rho^* l^{*2}. \tag{A14}$$

Also,

$$\begin{aligned}k/k' &= \rho^* l^*(lt'/l't)2\\ &= \rho^{*3} l^*(t'/t)2.\end{aligned} \tag{A15}$$

Therefore,

$$\begin{aligned}kt/k't' &= \rho^* l^{*3}(t'/t)\\ &= l^* \mu/\mu'.\end{aligned} \tag{A16}$$

Q.E.D.

Proof of Corollary 2.1

The equations of motion of a MSMS are given in representative values as follows:

$$f_m(t) = m\ddot{X}_m(t) + b\dot{X}_m(t) + k\ \delta X_m(t), \quad \text{(A17)}$$

$$f_s(t) = m\ddot{X}_s(t) + b'\dot{X}_s(t) + k'\ \delta X_s(t). \quad \text{(A18)}$$

From the conditions of physical similarity,

$$m^* = m/m' = 1, \quad \text{(A19)}$$

$$b^* = b/b' = v^*, \quad \text{(A20)}$$

$$k^* = k/k' = v^{*2}. \quad \text{(A21)}$$

Also, the requirement for physical similarity yields the following results:

$$\delta X_s(t) = \delta X_m(t/v^*), \quad \text{(A22)}$$

$$\dot{X}_s(t) = (1/v^*)\dot{X}_m(t/v^*), \quad \text{(A23)}$$

$$\ddot{X}_s(t) = (1/v^{*2})\ddot{X}_m(t/v^*). \quad \text{(A24)}$$

Therefore,

$$\begin{aligned} f_s(t) &= m'\ddot{X}_s(t) + b'\dot{X}_s(t) + k'X_s(t) \\ &= (m/v^{*2})\ddot{X}_m(t/v^*) + (b/v^{*2})\dot{X}_m(t/v^*) + (k/v^{*2})\delta X_m(t/v^*) \\ &= (1/v^{*2})\{m\ddot{X}_m(t/v^*) + b\dot{X}_m(t/v^*) + k\ \delta X_m(t/v^*)\} \\ &= (1/v^{*2})f_m(t/v^*). \end{aligned} \quad \text{(A25)}$$

Proof of Theorem 3

From Theorem 3, the physical similarity rules in real-time control ($t = t'$) are

$$\rho l^2/\mu = \rho' l'^2/\mu', \quad \text{(A26)}$$

$$k/\mu l = k'/\mu' l'. \quad \text{(A27)}$$

That is,

$$\mu/\mu' = \rho^* l^{*2}, \quad \text{(A28)}$$

$$k/k' = (\mu/\mu')l^{*3} = \rho^* l^{*3}, \quad \text{(A29)}$$

where

$$m = \rho l^3, \quad b = \mu l, \quad \text{(A30)}$$

which yields

$$m/m' = b/b' = k/k' = \rho^* l^{*3}. \quad \text{(A31)}$$

Also,

$$\begin{aligned} f/f' &= \{ml/t^2 + bl/t + kl\}/\{m'l'/t'^2 + b'l'/t' + k'l'\} \\ &= \rho^* l^{*3}(l/l')(1/t^2 + 1/t + 1)/(1/t'^2 + 1/t' + 1) \\ &= \rho^* l^{*4}. \end{aligned} \quad \text{(A32)}$$

Q.E.D.

APPENDIX B. PRESERVATION OF STABILITY OF THE PHYSICAL SIMILARITY TRANSFORMATION

By Laplace transformation of the equation of motion of the master system with Laplace operator s_1, the characteristic equation is

$$s_1^2 I + s_1 M^{-1} B + M^{-1} K = 0, \tag{B1}$$

and its stability conditions with the solution s_{1i} $(i = 1, \ldots, 6)$ are

$$\mathrm{Re}(s_{1i}) < 0, \quad i = 1, \ldots, 6. \tag{B2}$$

Similarly, with Laplace operator s_2, the characteristic equation of the slave system is

$$s_2^2 I + s_2 M'^{-1} B' + M'^{-1} K' = 0, \tag{B3}$$

and its stability conditions with the solution s_{2j} $(j = 1, \ldots, 6)$ are

$$\mathrm{Re}(s_{2j}) < 0, \quad j = 1, \ldots, 6. \tag{B4}$$

On the other hand, the motion velocity transformation yields the following relationship of time and dynamics of each system with the time ratio $t^* = t/t'(t)$ from (28) as

$$t^* = s_2/s_1. \tag{B5}$$

Also, from Theorem 2, the components m, b, k, m', b', and k' of the matrixes M, B, K, M', B', and K' have the following relationship:

$$k/m = k'/(m't^{*2}), \quad b/m = b'/(m't^*). \tag{B6}$$

Therefore, by substituting (B6) into (B1), the characteristic equation is

$$(t^* s_1)^2 I + (t^* s_1) M'^{-1} B' + M'^{-1} K = 0. \tag{B7}$$

From (B5) and (B7), the transformed master system is equal to the slave system. From (B5), the relationship of the solutions of each system is

$$s_{2i} = t^* s_{1i}, \quad i = 1, \ldots, 6; \tag{B8}$$

therefore the stability of the MSMS is preserved. Also, in the input/output force condition transformation, since the systems are equal to each other, the system stability is preserved.

Q.E.D.

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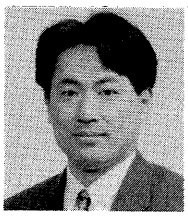

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