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# Impedance Scaling of a Tele-Existence Master-Slave Manipulation System by Using Similarity Transformation

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Abstract: *This research is concerned with extended force sensations of presence for tele-existence manipulation. 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/her to perform a remote manipulation dexterously with the feeling inside the slave anthropomorphic robot in the remote environment. In this paper, impedance-controlled master-slave manipulation system is presented as the basic system of extended bilateral teleoperators in different scale environments. Impedance scaling of size, power and time, is applied to the basic system to extend by using similarity transformation. The feasibility of the proposed method is demonstrated by experiments using a hardware direct-drive master manipulator and a software slave manipulator.*

Keywords: Tele-existence, Master-slave Manipulator, Impedance Scaling, Physical Similarity

## I. INTRODUCTION

### 1.1 Brief History of Teleoperators

The concept of remote operation of a machine arm by its operator, has been called teleoperator[23]. The earlier teleoperators mainly provided a control system from man to machine, while a feedback from machine to man was at a lower level where simple force information was fed back to the operator. A real sensation of presence for the operator to feel the existence inside the slave robot with visual, auditory, and tactile sensations, could not be provided in those systems. In the 1960s, an exoskeleton type of man-power amplifier machine had been studied in the U.S.[23] Although it had a sensation of presence, the robot technology was not very mature and the concept of operation within a robot still remained dangerous and negative to implement. In the 1970s, supervisory control was proposed as a combined concept of teleoperation and automatic control[24]. The idea has been used for teleoperation in space or in undersea operations to solve the problem of transmission time delay. These conventional teleoperators have enhanced the control system from man to machine, but have not generated a real sensation of presence.

The study on a feedback system of a sensation from machine to operator has been studied in the early 1980s in Japan and the U.S. independently. The technology is called tele-existence, telepresence or telerobotics. Tele-existence was proposed in MEL in the national project in Japan[25, ARTRA (Advanced Robot Technology Research Association). Telepresence was a concept reported in ARAMIS and has been studied in NASA[26].

### 1.2 Bilateral Control

One of the targets of a bilateral teleoperation is to realize an adequate bilateral response for an operator with both the forces and the motions of a manipulator[7,10,17,18]. In the conventional teleoperators; symmetry type, force-reflection type and force-feedback type, the operating performance is disturbed by their arm dynamics remaining in the system. In order to solve the problem, the regulation of the teleoperator's dynamics, have recently been studied by K.Kosuge et al. [8], K.Tanie et al. [9], T.Yoshikawa and Y.Yokokoji [10], J.Dudragne et al. [18], and B.Hanaford [17]. The teleoperator provides virtual arm dynamics for the operator, regulating the arm dynamics.

However the arm dynamics are fixed to some regulated values in these methods, and there are no mechanisms to change the arm dynamics for the adaptation according to a task or its environment, and to extend the operator's performance.

1.3 Tele-existence

The concept of mutually projecting the sensation and motion of both an operator and a robot by using cybernetic human interfaces, is called tele-existence. Tele-existence aims at the natural and efficient remote control of robots by feeding back abundant sensory information, which enables the operator to perform remote manipulation tasks dexterously with the vicarious feeling of being inside the slave anthropomorphic robot in the remote environment [1,2,25].

Systematic research for the development of tele-existence has been conducted at MEL on feeding back extensive sensory information. A tele-existence sensory display[1,2] and a mobile tele-existence vehicle, which is remotely driven with an auditory and visual sensation of presence, [3], have been constructed to evaluate the feasibility of the method.

In tele-existence, natural feedback of not only visual information but also kinesthetic information is necessary to allow an operator to feel a robot arm as his/her own arm. The tele-existence research group has developed an anthropomorphic robot with a seven degree-of-freedom arm and two cameras as a slave robot, a head-mounted display and a head-linked display for the master [4,5], and an *impedance-controlled master-slave manipulation systems* (impedance-controlled MSMS) to establish a bilateral control with kinesthetic feedback [7].

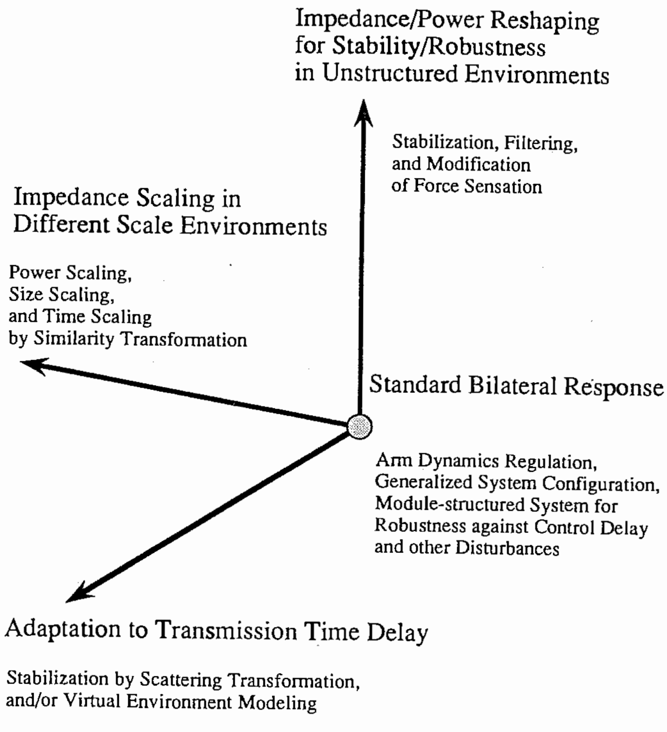


Fig.1 Standard bilateral teleoperation and its three extended directions.

1.4 Extended Sensation of Teleoperation

There are three directions of extended teleoperation from a standard bilateral control discussed in 1.2 (Fig.1).

The first direction is the main issue of this paper; the extended bilateral strategy in different scale environments. Teleoperation must be implemented not only in the ordinary case where manipulators are operated under the equivalent scale condition, but also in the case where the size, power and time scales of the master and slave systems are different from each other, such as in a micro-surgery. The stability condition in a different scale teleoperation such as "macro-micro bilateral manipulation, " has been studied by J.E.Colgate [22].

Second is the stabilization, filtering, and modification of the force sensation by impedance/power reshaping to assist the operation in an unstructured environment. Both environment and arm dynamics, represented as mechanical impedance, are simultaneously regulated in this strategy. H.Kazerooni has proposed a power assistance system, such as "extender"[21]. Also, J.E. Colgate has developed "impedance reshaping" of environment dynamics to keep robustness/stability in such an environment[22].

Third is the stabilization of transmission lines and/or modeling of the environment in time delay between master and slave systems. Time delay is one of the serious problems which destabilize a teleoperator. R.J.Anderson and M.W.Spong proposed scattering transformation to keep the system passive so as to stabilize it[19]. T.B. Sheridan et al.[20], and S.Tachi and T.Sakaki[7] proposed an alternative method using a real-time visual and/or force feedback by a virtual model of the environment in a master system.

In this paper, an extended impedance-controlled MSMS is presented, which comprises impedance scaling by physical similarity transformation of size, power and time scaling in different scale environments. This paper is organized as follows: Section II explains the principles of the standard impedance-controlled MSMS; Section III proposes the extended MSMS in different scale environments; Section IV shows the experimental results of the extended MSMS. The discussion and conclusions are presented in Section V.

## II. STANDARD IMPEDANCE-CONTROLLED MSMS

The impedance-controlled MSMS is a system in which the dynamics of the manipulators are regulated according to a target mechanical impedance, providing bilateral response (Fig.2). *Impedance control* deals with the dynamic interaction between a robot and its environment [6,11-13]. The fundamental concept of the control is also effective for the MSMS to deal with the robot and environment dynamics.

The master and slave impedances are available to be controlled independently in the MSMS. Any impedance control method can be applied to the controller according to the system configuration. For example, one of the implementation of impedance control is shown as follows [6]. The equation of motion of a manipulator are given as follows :

$$I\ddot{\Theta} + D_v\,\dot{\Theta} = T_a + J^T F_e \qquad (1)$$

where $I$ and $D_v$ are the inertia and viscosity matrices of the manipulator, respectively. $T_a$, $F_e$ and $\Theta$ are the actuator output torque, external force and rotational angle vectors, respectively, and $J^T$ denotes the transposed Jacobian. The target impedance is

$$F_e = M_o(\ddot{X} - \ddot{X}_o) + B_o(\dot{X} - \dot{X}_o) + K_o(X - X_o) \qquad (2)$$

where $(\ddot{X}_o, \dot{X}_o, X_o)$ are tartget motion of the manipulator. The torque in equation (3) is applied to realize the desired impedance of (2) as follows

$$T_a = (I - J^T M_o J)\,\ddot{\Theta} + (D_v - J^T M_o \dot{J} - J^T B_o J)\,\dot{\Theta}$$

$$+ J^T[M_o\ddot{X} + B_o\dot{X} + K_o(X_o - L(\Theta))] \qquad (3)$$

where $X = L(\Theta)$.

Now, the standard impedance controlled MSMS is controlled by the following scheme. The master and slave arms has apparently the same dynamics by the above impedance control from the supervisor's command. The equations of motion of the master and slave manipulators are described as follows:

$$F_o = M_o\ddot{X}_m + B_o\dot{X}_m + K_o X_m + F_1, \qquad (4)$$

$$F_2 = M_o\ddot{X}_s + B_o\dot{X}_s + K_o X_s + F_e. \qquad (5)$$

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

$$F_e = M\ddot{X}_s + B\dot{X}_s + K\,\delta X_s, \qquad (6)$$

where $(M_o, B_o, K_o)$ are the impedance parameters of the master and slave arms, and $(M, B, K)$ indicate the mechanical impedance parameters of the object. $F_o$ denotes the force exerted by the human operator. $F_1$ is the inner force command of the master manipulator. $F_2$ is that of the slave manipulator, and $F_e$ indicates the reflection force from the object. $X_m$ and $X_s$ denote the position vectors of the master and slave, respectively, and $\delta X_s$ is the position deviation vector of the object. Each parameter

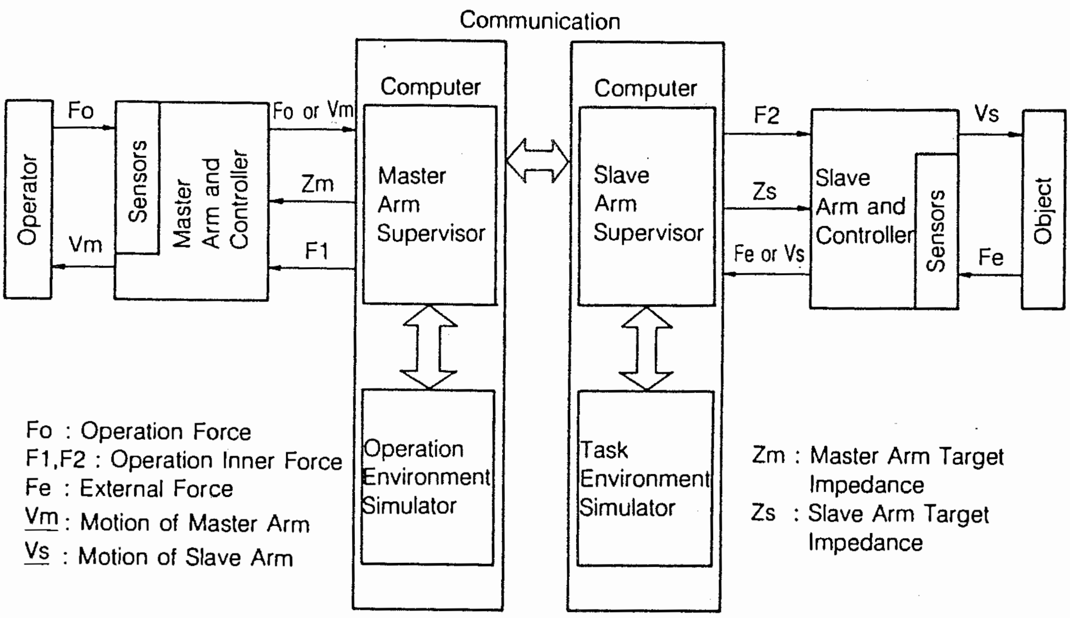


Fig.2 Standard impedance controlled MSMS.

of the impedance is a 6x6 matrix. Each position and posture of $X_m$ and $X_s$, and each force of $F_o$, $F_e$ and $F_1$ and $F_2$ is a 6x1 vector.

The *dual force transmission method* (D-F) is one of the previous impedance-controlled MSMS schemes[7]. In the D-F, the master manipulator transmits the operator's force to the slave arm controller, while the slave transmits the reaction force from the environment to the master arm controller by means of force/torque sensors. The equations of the master slave control strategies are:

$$F_1 = F_e, \quad (7)$$

$$F_2 = F_o. \quad (8)$$

Using this scheme, the positional error $e = X_m - X_s$ is represented by:

$$M_o \ddot{e} + B_o \dot{e} + K_o e = 0. \quad (9)$$

Since the error $e$ is reduced to zero according to the appropriate mechanical impedance parameters ($M_o$, $B_o$, $K_o$ ), and the relationship between the operation force and the reaction force becomes,

$$F_o = (M_o \ddot{X} + B_o \dot{X} + K_o X) + F_e. \quad (10)$$

If we select a small and known target impedance, $F_o$ becomes very close to $F_e$, and the operator can feel the object in direct manipulation. Note that the stability problem in the case of contact to a rigid environment is not considered in this case, which will be discussed in Section V.

## III. IMPEDANCE SCALING IN DIFFERENT SCALE ENVIRONMENTS

### 3.1 Teleoperation in Different Scale Environments

Tele-existence manipulation aims not only at ideal teleoperation for the direct manipulation of an object in an equivalent scale environment, but also at the extension of operation capability in different scale environments, where the scales of a slave manipulator and its environment, are extremely different from those of a master arm and its environment, such as a micro-surgery to manipulate a cell, a long slowly-driven space manipulator, or a robot arm for construction or maintenance with amplification of the operator's force.

In conventional strategies, the control of these arms has not dealt with a unified approach to physical similarity. The information transformed between bilateral manipulators only by geometrical similarity, does not always match physical phenomena. J.E.Colgate has discussed the stability and robustness of "macro-micro bilateral manipulators" by using "impedance reshaping" [22]. However, the regulation of performance between master slave manipulators has not been discussed. Machida et al. has proposed transforming mapping of the operator motion to a space manipulator motion by a task rearrangement such as editing a videotape [15]. However, the plan of dynamic control of the robot arm deals only with the time history of arm motion.

In different scale environments, physical similarity should be satisfied in the extended MSMS operation so that the dynamic motion and force of master and slave arms are considered as physical phenomena.

***Size and power scalings*** ——The transformation of size and power scales provides an extended bilateral operation so that the operator has the sensation of presence in size and/or power of the slave robot (Fig.3). For instance, the force sensation operating a blood vessel during a micro-surgery can be vicariously transformed to the force sensation manipulating a rubber tube, helping a surgeon to manipulate the tube more easily.

***Time scaling*** —— In a teaching mode of the master-slave manipulators, it is difficult for the operator to achieve a task directly at extremely fast or slow speeds of the machine. The transformation of time scale can be applied to the teaching mode, in the case where the task is a predetermined one and the dynamics of the environment will not change quickly. The mode is not a bilateral one, but a pseudo-bilateral sensation is available to the operator in the teaching mode using a simulation of environment dynamics. After that the teaching motion is transformed with expansion/compression in time scale to that of a new command for the slave system.

### 3.2 Extension of Operation Capability by Applying Physical Similarity Transformation

In impedance scaling in different scale environments, not only the geometrical relationship but also physical similarity must be satisfied in both master and slave manipulator dynamics.

***Scaling rule*** is a rule used in a model experiment to estimate data of a real phenomena from those of a model phenomena, transforming them not only in geometrical size but also in each physical coefficient[14]. Physical similarity is defined as all variables (size, time, velocity, force, ...) in a model phenomena are similar to its real phenomena. It means the similarity of each *corresponding variable* is as follows

$$q^* = \frac{q_1}{q_1'} = \dots = \frac{q_i}{q_i'} = \dots. = \frac{q_r}{q_r'} = \dots. = \frac{q_n}{q_n'} \quad (11)$$

where $q_1$ ... $q_n$ indicate the variables of real phenomena (such as each size of a real object) and $q_1'$ ... $q_n'$ are the variables of model phenomena (such as each size of a model object), and $q^*$ is a scale factor. The similarity is also defined by $\pi$-*number* which is defined as

$$\pi = \frac{q_i}{q_r}, \qquad \pi' = \frac{q_i'}{q_r'} \quad (12)$$

The similarity condition is defined as $\pi = \pi'$. It shows that $\pi$-number, which represents a ratio of all of the same kinds of variables of real phenomena in the same kind, is equal to the ratio of those of a model. In order to derive a scaling rule, physical rules which dominate a real phenomena, should be considered as dominating rules in a model one.

Now, the scaling rule is applied to the case of an MSMS. Assume the dominating physical rules are the following three rules:

Rule of inertia: $f_i = m\,\alpha = \rho\, l^4/t^2$, (13)

Relationship of viscosity: $f_v = b\,v = \mu\, l\, v = \mu\, l^2/t$, (14)

Relationship of stiffness: $f_k = k\,l$, (15)

where $r$, $l$, $m$ and $t$ indicate representative quantities, representing the variables of density, scale, viscosity and time, respectively. Null-dimensioning them by $\pi$-numbers [14], those numbers are,

$$\pi_1 = f_i\ / f_v\ = \rho\, l^2 / (\mu\, t), \quad (16)$$

$$\pi_2 = f_k\ / f_v\ = k\, t\ / (\mu\, l), \quad (17)$$

where each slave parameter is described by adding " ' " to the corresponding master parameter. Note that the master and slave dynamics are equal to each other ($m = m'$, $b = b'$, $k = k'$), physical similarity is naturally satisfied ($\pi_1 = \pi_1'$, $\pi_2 = \pi_2'$).

(1) The real force sensation of presence in *size and power scaling* is provided by a transformation of the size and input/output force conditions, considering not only the geometrical ratio but also the physical similarity of both master and slave dynamics.

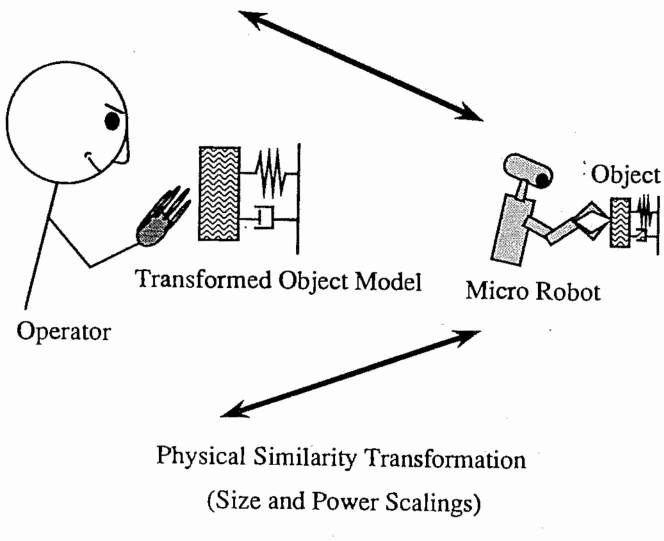


Fig.3 Extension of force sensation of presence in size and power scaling by physical similarity transformation.

**[Theorem 1]** When the geometrical similarity ratio $l^*$ in both manipulators is given, the impedance scaling to decide the ratio of each physical specification (density, viscosity, and stiffness) exists to satisfy a physical similarity rule, transforming the ratio of the input/output force condition. If the geometrical similarity ratio $l^*$, and either the density ratio $\rho^*$, the viscosity ratio $\mu^*$ or the stiffness ratio $k^*$ are given, then the impedance scaling of both manipulator dynamics is determined. For instance, the impedance scaling according to $\rho^*$ is as follows:

$$m / m' = b / b' = k / k' = \rho^* l^{*3}. \quad (18)$$

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

$$f / f' = \rho^* l^{*4}, \quad (19)$$

where

$$l^* = l / l', \quad \rho^* = \rho / \rho', \quad \mu^* = \mu / \mu', \quad k^* = k / k'. \quad (20)$$

In the geometrically equivalent scale conditions ($l^* = 1$), the transformation of the input/output forces is considered

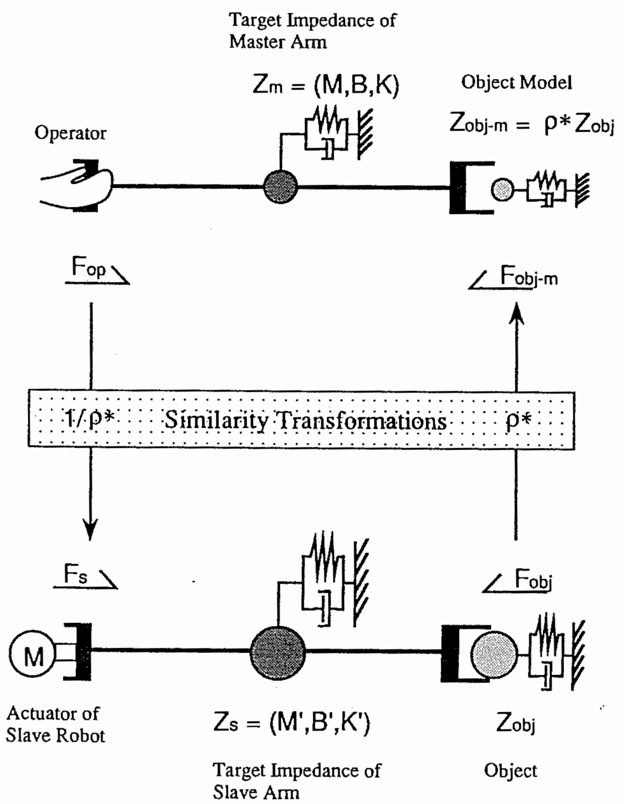


Fig.4 Impedance scaling of power in equivalent size scale.

as *power scaling* by the following impedance scaling (See Fig.4).

**[Corollary 1-1]** In the MSMS which satisfies Theorem 1 in the case of $l^* = 1$, if the density ratio $\rho^*$ is given as the transformation ratio of both manipulator dynamics,

$$m/m' = b/b' = k/k' = \rho^*, \quad (21)$$

the time history of both the master operation force $f_m(t)$ and the slave inner force command $f_s(t)$ are represented by the following force transformation ratio:

$$f/f' = \rho^*, \quad (22)$$

Note that the corollary can be easily extended for arbitrary $\rho^*$ and $l^*$.

(2) The extension of the operation capability is considered in the transformation of the task-motion velocity by *time scaling*. When it is difficult to execute a task at the desired motion velocity, the motion of the master in the teaching mode is transformed to the command of the slave at the desired velocity.

**[Theorem 2]** When the geometrical similarity ratio $l^*$ and the density ratio $\rho^*$ are given, physical similarity is satisfied in impedance scaling according to the velocity ratio $v^*$ of both arm motions:

$$m/m' = \rho^* l^{*3}, \quad b/b' = \rho^* l^{*2} v^*, \quad k/k' = \rho^* l^* v^{*2}. \quad (23)$$

The transformation of motion velocity is considered as a transformation of the master operation torque to the slave inner torque.

**[Corollary 2-1]** In the MSMS which satisfies the physical rule of motion velocity (Theorem 2), assuming $\rho^* = 1$, and $l^* = 1$ for simplicity, if the motion velocity ratio $v^*$ is given, the time history of both the master operation force $f_m(t)$ and the slave inner force $f_s(t)$ are represented by the following relationship:

$$f_s(t) = (1/v^{*2}) fm(t/v^*). \quad (24)$$

Note that this corollary can be easily extended for arbitrary $\rho^*$ and $l^*$.

The proposed MSMS provides to an operator with an extended sensation of presence with physical generality established by impedance scaling to satisfy physical similarity rules in the time, size and power scalings.

## IV. SIMILARITY TRANSFORMATION EXPERIMENTS

### 4.1 Experimental Setup

A direct-drive manipulator with two d.o.f. was used as a master manipulator [6]. The slave manipulator and the object were simulated as a dynamic model in a computer. The mechanical impedances of the two degree-of-freedom of the manipulator (vertical and horizontal directions) were controlled by a torque-based impedance control as shown in Section II (Fig.5). Each joint of the manipulator was driven by a direct-drive DC motor (Inland Co.) and an encoder of 2000 P/R with a four-time frequency multiplier, applied to an up/down counter of the rotational angle. Each pulse interval was measured by a 12 bit timer counter with a clock of 500 kHz. The reciprocal of the interval multiplied by the rotational angle for one pulse interval, was also used as the estimated value of the angular velocity. Second-order digital low pass filters were also applied to estimate the angular velocity and the angular acceleration. A microprocessor (Intel 80386 20 MHz with 80387 coprocessor) calculated the necessary torque to attain the desired impedance, and fed it to servo-amps to control the manipulator. A program was written in the language C and the sampling time was less than 3 ms.

Figure 6 shows the configuration of the simulator. The target impedances were assigned both into the master and slave controllers. The dynamics models of the slave manipulator and its object were given in the computer. When the master manipulator is operated manually, the dynamic responses of the master and slave manipulators are measured. When the master arm, controlled by the impedance control in equations (1)-(3), is operated, its motion (position, velocity and acceleration) $X_m$ is measured. The operation force $F_o$ is derived from $X_m$ and the control input $F_1$ transmitted from the slave system and provided to the operator. The control input $F_2$ is sent

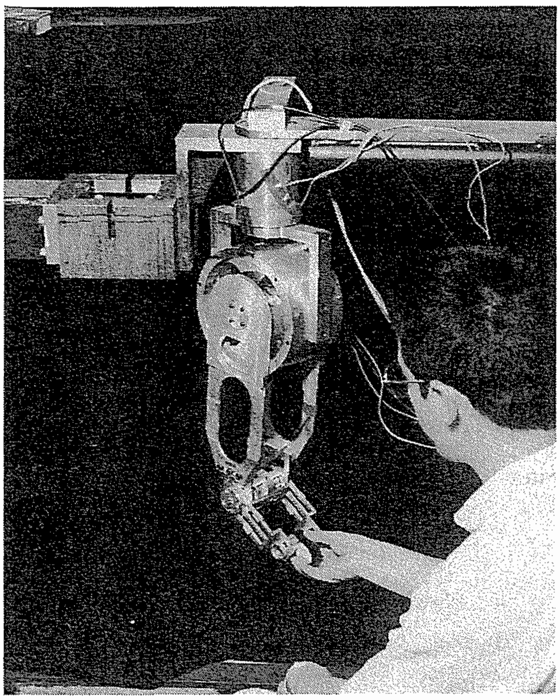

Fig.5 Experimental setup of impedance controlled master arm.

to the slave system. During the transmission $F_2$ is transformed to $F_2'$ by the scaling rules of control input (19) or (24). $F_2'$ is sent to the slave system. The slave arm and its environment are simulated under the condition that the slave arm completely contacts its environment. The slave system generates its arm motion $X_s$ from $F_2'$, and send $X_s$ to the environment dynamics (6) to get the external force $F_e$. the slave system sends the control input $F_1'$ to the master system from $F_e$. $F_1'$ is transmitted to $F_1$ and fed to the master system. Note that since the purpose of the experiments is to examine the transformation system of physical similarity, the dynamics of the environment are set simple and linear and contact stability problem on a rigid environment is not considered.

4.2 Experiment of Similarity Transformation of Sensation in Size and Power Scalings

The size and power transformations were investigated experimentally using Theorem 1. The impedance parameters of the master arm and its object model were given as follows

$$M_o = 0.05 \text{ [kg]},\ B_o = 1.0 \text{ [N/(m/s)]},\ K_o = 0.1 \text{ [N/m]},$$
$$M = 0.01\text{[kg]},\quad B = 5.0 \text{ [N/(m/s)]},\quad K = 5.0 \text{ [N/m]}.$$

and the conditions of size/power scale were given as $\rho^* = 2$ and $l^* = 10$. By (18)-(20), the slave impedance parameters were derived as $1/\rho^* l^{*3}$ (= 1/2000) times the master parameters. Figure 7 shows the time histories of the position and force of both arms. The scale of the position of the master is set as from - 0.2 to 0.2 [m], and that of the slave as from - 0.02 to 0.02 [m] in the figure. Also, the scale of the force of the master is set as from - 2.0 to 2.0 [N], and that of the slave as $-1.0{*}10^{-4}$ to $1.0{*}10^{-4}$ [N]. The slave arm was controlled to the position of $1/l^*$ (= 1/10) times the master, and the force of $\rho^* l^{*4}$ (= 2000) times the slave was reflected to the operator.

4.3 Experiment of Similarity Transformation of Sensation in Time Scaling

The transformation of motion velocities of the master-slave arms in time scaling applied by Theorem 2 and Corollary 2-1, was conducted experimentally as follows.

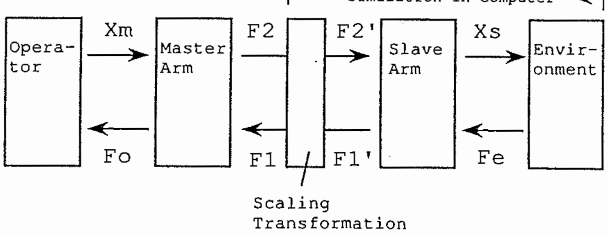


Fig.6 Scaling transformation simulator.

When the ratios $\rho^* = 1$, $l^* = 1$ and the motion velocity ratio $v^* = 2/3$ were given, the compressed scaling of time is $v^*$ (= 2/3). By Corollary 2-1, the target impedance parameters of the slave arm were derived as,

$$M_s = 0.5 \text{ [kg]},\ B_s = 30.0 \text{ [N/(m/s)]},\ K_s = 90.0 \text{ [N/m]},$$

according to the target impedance of the master

$$M_o = 0.5 \text{ [kg]},\ B_o = 20.0 \text{ [N/(m/s)]},\ K_o = 40.0 \text{ [N/m]}.$$

By (23) and (24), master operation force and the transformed force as the slave force command, were determined with these parameters. The slave arm was simulated by software 5 seconds after the DD arm was operated as a master arm. Figure 8 shows the time histories of both the master operation force and position of the DD arm, and the simulated slave inner torque and position. For comparison simplicity, the start times of both arm motions are coincident in the figure. The slave arm executed a compressed motion according to $v^*$ (= 2/3), maintaining the impedance scaling (same as time scaling).

## V. DISCUSSION AND CONCLUSIONS

This paper presented a new master-slave manipulators with an extended force sensation in tele-existence. Impedance control and scaling rule have been applied to the MSMS. According to the transformation of size, power or time scale applied with impedance control and physical similarity, the force sensation in the MSMS is extended to rearrange the operation capability in different scale environments.

The proposed method has been verified by simulations using DD master arm and software slave arm and environment. Although the dynamics model in the simulations is a simple linear mechanical impedance one, it is sufficient to show the verification of the transformation method. No dynamics model of environment is necessary for the MSMS in the size and power scaling. The factors of the transformation $\rho^*$ and $l^*$ will be set according to master/slave environments physical coefficients from (18). Those factors determine the force/motion sensitivity between the master and slave operations from (19). The time scaling, which should be used for predetermined works in off line, will require some dynamics model of environment in the case of applying some force control to its object. Therefore the standard bilateral MSMS should be utilized for more complicated work or environment instead of the application of the time scaling.

The contact stability to an stiff environment was not dealt with in the simulation. The stability is beyond the scope of this paper. However the proposed method in this paper will be combined with the stabilization method as one of the other extending direction of MSMS as shown in Section I such as [22]. The future topics are the development of new schemes along other extension directions, and combined systems of those extensions.

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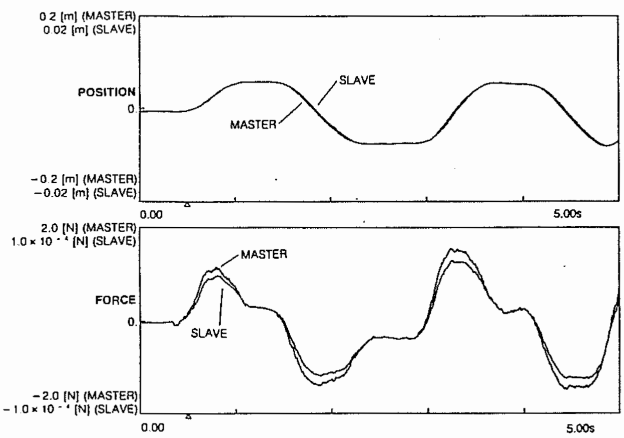


Fig.7 Experimental results of size and power scalings by similarity transformation.

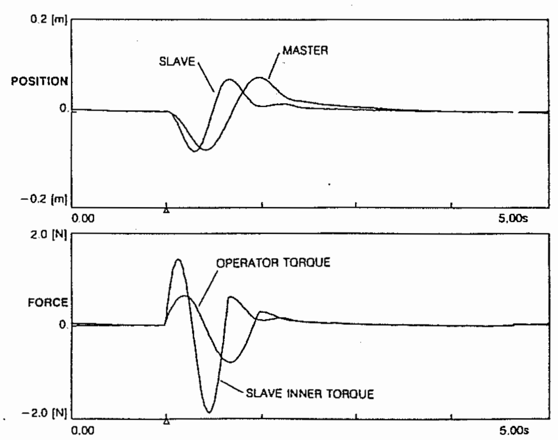


Fig.8 Experimental results of time scaling (compression) by similarity transformation.

Note: $\rho^* = 2$, $l^* = 10$.
Master impedance parameters;
$Mo = 0.05$ [kg], $Bo = 1.0$ [N/(m/s)], $Ko = 0.1$ [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 $1/r^* l^{*3} = 1/2000$ times of impedance parameters in master system.

Note: Transformed slave motion is simulated offline.
($\rho^* = 1$, $l^* = 1$, $\nu^* = 2/3$)
Master impedance parameters;
$Mo = 0.5$ [kg], $Bo = 20.0$ [N/(m/s)], $Ko = 40.0$ [N/m].
Slave impedance parameters;
$Ms = 0.5$ [kg], $Bs = 30.0$ [N/(m/s)], $Ks = 90.0$ [N/m].