Proceedings of the 1993 JSME
International Conference on Advanced Mechatronics
Tokyo, JAPAN - Aug. 1993

Tele-Existence Virtual Dynamics Display Using Impedance Scaling with Physical Similarity

Taisuke Sakaki* Yasuyuki Inoue* Susumu Tachi**

*Tsukuba Research Laboratory, Yaskawa Electric Corporation
5-9-10 Tokodai, Tsukuba Science City, Ibaraki, 300-26, Japan.
**RCAST, University of Tokyo
4-6-1 Komaba, Meguroku, Tokyo, 153, Japan.

This research presents virtual dynamics display for tele-existence manipulation between different scale environments. Previous teleoperators have dealt only with the geometrical similarity and have ignored the similarity of dynamics between those environments. The proposed master-slave manipulators executes the similarity transformation of physical scales such as size and/or force with using impedance scaling. The virtual dynamics display provides the operator with the dynamics information of scaled size and/or force. It results the slave environment apparently appears to the operator as a virtually scaled environment dynamics. The dynamics display enables the extended teleoperating sensation in different scale environments such as micro teleoperation or man-power amplifier.

I. INTRODUCTION

1.1 Teleoperation

The remote operation of a machine arm by its operator has been called teleoperator[1]. The earlier teleoperators had been constructed as a control system mainly from man to machine, in which simple force information was fed back to the operator. In the 1960s, an exoskeleton type of man-power amplifier machine had been studied in the U.S.[1] Although it had a sensation of presence, the concept of operation within a robot still remained dangerous and negative to implement because of its primitive robotics technology. In the 1970s, supervisory control was proposed as a combined concept of teleoperation and automatic control[2]. The idea has been used for teleoperation in space and in undersea to solve the problem of transmission time delay. Although these conventional teleoperators have enhanced the control system from man to machine, they have not generated real sensation of presence from machine to operator.

The concepts of real time sensation of presence have been proposed since the early 1980s in Japan and the U.S. independently. The technology is called tele-existence or telepresence. Tele-existence has been proposed at MEL in the national project of ART (Advanced Robot Technology) in Japan[4]. Telepresence is a concept reported in ARAMIS[3] and has been studied in NASA. In these teleoperation systems, varieties of sensations such as force, motion, visual, auditory and tactile ones are transmitted between an operator and a robot through computers in real time.

1.2 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[4-11]. 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. In tele-existence, natural feedback of not only visual information but also kinesthetic information is provided to the operator to feel a robot arm as his/her own arm. Systematic research for the development of tele-existence has been conducted at MEL on feeding back extensive sensory information. Tele-existence sensory displays[5,6], and a mobile tele-existence vehicle remotely driven with an auditory and visual sensation of presence[7] have been constructed to evaluate the feasibility of the technology.

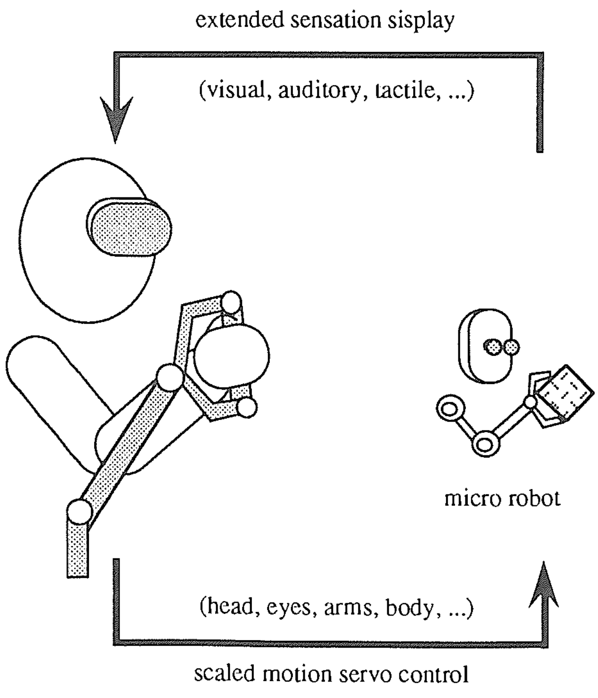


Fig.1 Tele-existence with sensation extended on scales.

1.3 Bilateral Control

Bilateral teleoperation, one of the functions of teleoperator aims to realize real force response to an operator. In the conventional bilateral teleoperators (symmetry type, force-reflection type and force-feedback type), the operating performance is disturbed by their arm dynamics remaining in the systems. In order to solve the problem, the regulation of the teleoperator's dynamics, has recently been studied[12-18].

The tele-existence research group has also 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[8,9], and impedance-controlled master-slave manipulation system to establish a bilateral control with kinesthetic feedback, regulating both arm impedances independently[10].

1.4 Scaled Teleoperation

The previous teleoperators have not dealt with the teleoperation between environments with different scales. The arm dynamics have been fixed to some regulated values, and there have been no mechanisms to change the arm dynamics for the adaptation and extension of the operator's performance according to a task and its environment.

The scaled tele-manipulation is operated under the condition 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, a construction robot with amplification of the operator's force, and so on. The teleoperation has not been considered with physical similarity as dynamic relationship between those environments except with geometrical similarity. J.E.Colgate has discussed the stability and robustness of "macro-micro bilateral manipulators" by using "impedance reshaping"[19]. However, there is little arguments on the scaling method of size and force to regulate bilateral performance between master-slave manipulators. K.Machida et al. have proposed a mapping of the operator motion to a space manipulator motion by task rearrangement such as arrangement of a videotape[20]. The motion editor deals with the time history of the arm task. However, the dynamic flow of the robot tasks as physical phenomena, has been disregarded in the system.

This paper presents the teleoperator to realize the extended bilateral control between different scale environments [11]. Impedance scaling of each arm virtual impedance is applied to the master-slave system to conserve the physical similarity between the environments. the teleoperator works as a tele-existence virtual dynamics display so that the slave environment appears to the operator as the virtually augmented dynamics through scale transformation. The transformation of size and force scales will provide extended bilateral operation so that the operator has the sensation of presence in scaled size and/or force of the slave robot (Fig.1). For instance, the force sensation operating a blood vessel during micro-surgery can be vicariously transformed to the force sensation manipulating a rubber tube, helping a surgeon to manipulate the tube more easily. This paper is organized as follows: Section II explains the principles of the impedance scaling and its implementation to the virtual dynamics display with extended bilateral sensation; Section III shows the experimental results of the scaled teleoperation. Section IV is the discussion.

II. IMPEDANCE SCALING IN TELEOPERATION BETWEEN DIFFERENT SCALE ENVIRONMENTS

2.1 Physical Similarity between Different Scale Environments

Both geometrical and physical similarities must be satisfied in bilateral control in different scale environments. The general conditions for physical similarity between master-slave control are derived from scaling rule. Scaling rule is a rule used in model experiment to estimate data of real phenomena from those of a model phenomena, transforming them not only in geometrical size but also in each physical coefficient with physical similarity[21]. Physical similarity is defined that all independent variables (size l, time t, force f, ...), which are called corresponding variables, in model phenomena are physically similar to those of its real phenomena. The similarity of each corresponding variable is shown as follows

$$q^* = \frac{q_{M1}}{q_{S1}} = \ldots = \frac{q_{Mn}}{q_{Sn}}, \quad \text{for } q = l, t, f, \ldots \tag{1}$$

where q_{M1} ... q_{Mn} indicate the values of a corresponding variable of real phenomena (such as each size of a real object) and q_{S1} ... q_{Sn} are the values of the variable of model phenomena (such as each size of a model object), and q^* is the scale factor of the variable. A scale factor exists for each corresponding variable.

Now, we will derive the principle of a scaled teleoperation between different scale environments. For simplicity, we consider the following three physical rules with the corresponding variables of inertia, viscosity, stiffness and force:

Rule of inertia: $$f_i = m\,a = \frac{\rho\, l^4}{t^2}, \tag{2}$$

Relationship of viscosity: $$f_v = b\,v = m\,l\,v = \frac{m\,l^2}{t}, \tag{3}$$

Relationship of stiffness: $$f_k = k\,l, \tag{4}$$

where ρ, l, m and t indicate representative quantities, representing the variables of density, size, inertia and time, respectively. π-number indicates the relationship between physical rules in phenomena. The π-numbers of the physical rules (2)-(4) are,

$$\pi_{M1} = \frac{f_{Mi}}{f_{Mv}} = \frac{\rho_M\, l_M^2}{m_M\, t_M}, \quad \pi_{M2} = \frac{f_{Mk}}{f_{Mv}} = \frac{k_M\, t_M}{m_M\, l_M}, \tag{5}$$

for the master arm phenomena, and

$$\pi_{S1} = \frac{f_{Si}}{f_{Sv}} = \frac{\rho_S\, l_S^2}{m_S\, t_S}, \quad \pi_{S2} = \frac{f_{Sk}}{f_{Sv}} = \frac{k_S\, t_S}{m_S\, l_S}, \tag{6}$$

for the slave arm phenomena. The similarity condition of both phenomena is that all of the corresponding π-numbers are equal to each other:

$$\pi_{M1} = \pi_{S1}, \quad \pi_{M2} = \pi_{S2}, \tag{7}$$

or

$$\rho^*\, l^{*2} = m^*\, t^*, \quad k^*\, t^* = m^*\, l^*. \tag{8}$$

Since the impedance parameters are represented as follows:

$$m = \rho\, l^3,\quad b = \frac{\rho\, l^3}{t},\quad k = \frac{\rho\, l^3}{t^2}\ , \tag{9}$$

the similarity conditions in different scale teleoperation are

$$\frac{m_M}{m_S} = \rho^*\, l^{*3},\quad \frac{b_M}{b_S} = \frac{\rho^*\, l^{*3}}{t^*},\quad \frac{k_M}{k_S} = \frac{\rho^*\, l^{*3}}{t^{*2}}\ , \tag{10}$$

where

$$l^* = \frac{l_M}{l_S},\quad \rho^* = \frac{\rho_M}{\rho_S},\quad t^* = \frac{t_M}{t_S}\ . \tag{11}$$

Also, since the representative quantities of each output force are indicated as the following second order systems:

$$f_M = \frac{m_M\, l_M}{t_M^2} + \frac{b_M\, l_M}{t_M} + k_M\, l_M\ , \tag{12.a}$$

$$f_S = \frac{m_S\, l_S}{t_S^2} + \frac{b_S\, l_S}{t_S} + k_S\, l_S\ , \tag{12.b}$$

by the similarity condition (10), the force scale factor will be

$$f^* = \frac{f_M}{f_S} = \frac{\dfrac{m_M\, l_M}{t_M^2} + \dfrac{b_M\, l_M}{t_M} + k_M\, l_M}{\dfrac{m_S\, l_S}{t_S^2} + \dfrac{b_S\, l_S}{t_S} + k_S\, l_S} = \frac{\rho^*\, l^{*4}}{t^{*2}}\ . \tag{13}$$

In order to satisfy the physical similarity of both master and slave dynamics, the force scale factor between the manipulators should be

$$f^* = \frac{f_M}{f_S} = \frac{\rho^*\, l^{*4}}{t^{*2}}\ . \tag{14}$$

2.2 Bilateral Control with Impedance Scaling and Virtual Dynamics Display

In this section, we will describe the impedance scaling in size and force. The implementation method of the scaling to real-time bilateral control and the effect of virtual dynamics display to the operator will be proposed. For simplicity, one d.o.f. case will be considered.

A second order system of mechanical impedance is represented in time domain as follows:

$$f = m\,\ddot{x} + b\,\dot{x} + k\,x, \tag{15}$$

where f is the external force, x is the manipulator position, and m, b and k are the impedance parameters: inertia, viscosity and elasticity, respectively. Hence, the system in frequency domain is

$$F(s) = Z(s)\,X(s), \tag{16}$$

where the impedance is

$$Z(s) = m\,s^2 + b\,s + k = \mathbf{z}\,\mathbf{s}. \tag{17}$$

We define the impedance vector $\mathbf{z}$ and the Laplace transformation vector $\mathbf{s}$ respectively as

$$\mathbf{z} = [\,m\ \ b\ \ k\,],\quad \mathbf{s} = \begin{bmatrix} s^2 \\ s \\ 1 \end{bmatrix}, \tag{18}$$

and define each target impedance vector of the master and slave arms as

$$\mathbf{z}_M = [\,m_M\ \ b_M\ \ k_M\,],\quad \mathbf{z}_S = [\,m_S\ \ b_S\ \ k_S\,], \tag{19}$$

respectively. From the scaling conditions (10), the similarity of the impedances is represented as follows:

$$\mathbf{z}_M = \mathbf{z}^*\,\mathbf{z}_S\ , \tag{20}$$

where $\mathbf{z}^*$ indicates the impedance scaling matrix:

$$\mathbf{z}^* = \begin{bmatrix} \rho^*\, l^{*3} & 0 & 0 \\ 0 & \dfrac{\rho^*\, l^{*3}}{t^*} & 0 \\ 0 & 0 & \dfrac{\rho^*\, l^{*3}}{t^{*2}} \end{bmatrix}. \tag{21}$$

Note that in bilateral control the matrix is represented as the following scalar value:

$$z^* = \rho^*\, l^{*3}, \tag{22}$$

which is called impedance scaling factor. Since the scaled teleoperation is a real time bilateral control, the time scaling factor t^* is equal to 1.

In scaled teleoperation, we must determine four similarity factors: size scaling factor l^*, density scaling factor ρ^*, impedance scaling factor z^*, and force scaling factor $f^* = f_M/f_S = \rho^* l^*$. There are four methods for the assignment of those factors as follows:

a) The assignment of the size and density factors, l^* and ρ^* will lead the impedance scaling factor z^* and force scaling factor f^*.

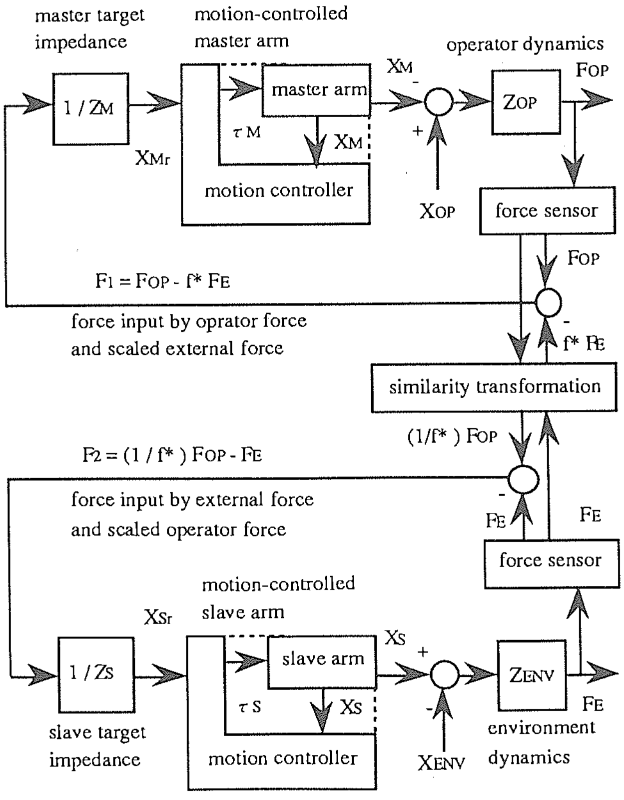


Fig.2 Scaled master-slave control system.

b) The assignment of the force factor f^* and either l^* or ρ^* will derive the impedance scaling factor z^* and the rest of the factors, ρ^* or l^*.

c) The assignment of the scaling factor z^* and either l^* or ρ^* will yield the force scaling factor f^* and the rest of the factors, ρ^* or l^*.

d) The assignment of the scaling factor z^* and the force scaling factor f^* will yield the scaling factors l^* and ρ^*.

We will describe the control algorithm to implementation to the master-slave manipulators based on motion servo control (Fig.2).

1) The scaling conditions in bilateral control yields to the scaling factor of target impedance:

$$z^* = \frac{f^*}{l^*} . \tag{23}$$

2) The following shows one of the assignment processes of control parameters in the scaled teleoperation according to the assignment process b). To begin with, assign the slave target impedance Z_S:

$$Z_S = z_S\, s = m_S\, s^2 + b_S\, s + k_S . \tag{24}$$

Then, assign the scale factors of size and force, l^* and f^*. They yield to the scale factor of impedance: $z^* = f^* / l^*$. Hence, the target impedance of master will be derived as follows,

$$Z_M = z^*\, Z_S = z^*\, (m_S\, s^2 + b_S\, s + k_S). \tag{25}$$

3) Now, the scaled teleoperation executes the following process. First, the control input is derived from the operational force Fop and the external force Fe. The force scale factor f^* is used for the similarity transformation of those force information:

$$F_1 = F_{op} - f^*\, F_e, \quad F_2 = \frac{F_{op}}{f^*} - F_e . \tag{26}$$

Secondly, F_1 and F_2 are fed to the digitized target impedance equation to get each target trajectory of master and slave, X_{Mr} and X_{Sr}. According to the impedance equations (16), (24) and (25), the following digital equations are derived to draw the target trajectories,

$$x_M(k + 1) = P_M\, x_M(k) + q_M\, u_M(k), \tag{27.a}$$

$$x_M(k) = \begin{bmatrix} x_{M1}(k) \\ x_{M2}(k) \end{bmatrix}, \tag{27.b}$$

$$u_M(k) = \frac{F_1}{m_S\, z^*}, \tag{27.c}$$

$$X_{Mr}(k) = [\ 1 \quad 0\ ]\, x_M(k), \tag{27.d}$$

for master manipulator, and

$$x_S(k + 1) = P_S\, x_S(k) + q_S\, u_S(k), \tag{28.a}$$

$$x_S(k) = \begin{bmatrix} x_{S1}(k) \\ x_{S2}(k) \end{bmatrix}, \tag{28.b}$$

$$u_S(k) = \frac{F_2}{m_S}, \tag{28.c}$$

$$X_{Sr}(k) = [\ 1 \quad 0\ ]\, x_S(k), \tag{28.d}$$

for slave manipulator. Thirdly, the master and slave manipulators controls their motions to follow the trajectories, X_{Mr} and X_{Sr}, with their motion servo controllers, respectively.

The scaling of size, force and target impedance satisfies the physical similarity between master and slave dynamic motions. It results in a virtual environment dynamics z_{EM} to appear in real time to the operator (See Fig.3). This virtual environment has a relationship with the actual environment z_E as follows:

$$z_{EM} = z^*\, z_E . \tag{29}$$

The system will help the operator to execute a task with an extended real-time sensation of presence to manipulate the virtual environment.

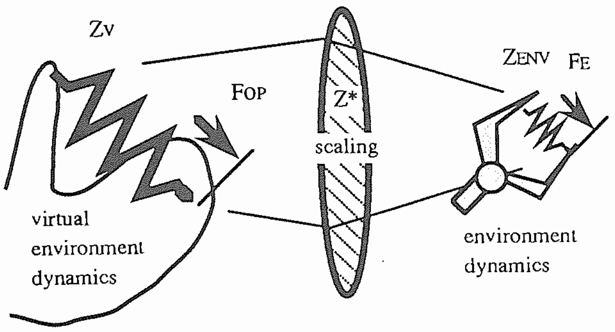


Fig.3 Effect of virtual dynamics display in scaled teleoperation.

III. EXPERIMENTS OF VIRTUAL DYNAMICS DISPLAY IN SCALED TELEOPERATION

3.1 Experimental Setup

Two linear sliders with one d.o.f. are used as master-slave manipulators (Fig.4). Each slider mounts a DC servo motor with an encoder of 1000 P/R. The motor driver controls the servo motor torque according to the torque command from the computer. A force sensor mounted on the sliding table detects the force applied to the end-effector along the sliding axis. An desktop computer (80386 + 80387) includes A/D, U/D and A/D boards. The A/D board is provided with the force sensor information from the force sensors. The U/D board is supplied with the rotational angle information of the encoders. The D/A board feeds the torque command to the motor drivers. The operator assigns a pair of target impedances and the scale factors. Second-order digital low pass filter is applied to estimate the velocity of sliding table motion with the motor rotational angle. The microprocessor calculates the reference position of the tables by the algorithm of motion-based impedance control with force sensor information, position and velocity information of the tables. The servo control of the table motion derives the necessary torque to attain the desired impedance. The torque command of servo control is fed to the motor driver to control the table position. The servo system consists of the PI velocity control and P position control. The sampling time of the program is 2 ms.

3.2 Experiment of Scaling Teleoperation

The following experiments will show the effect of the extended teleoperation with the scaled sensation of size and force. In these experiments, the slave manipulator works as a micro-manipulator and the master manipulator has the function of a virtual dynamics display to amplify the dynamic sensation in contact to the object dynamics with the slave manipulator.

1) Experiment 1: Amplification of force sensation. According to the algorithm of the scaling teleoperation shown in 2.2, we will derive the scaling factors. In the case of the force scaling factor, $f^* = 2$, and the size scaling factor, $l^* = 1$, which indicate the amplifying ratio from slave to master respectively, then the impedance scaling factor is derived as $z^* = f^* / l^* = 2$. In this experiment, the slave target impedance is assigned as z_S = (1 [kg], 20 [N/(m/s)], 10 [N/m]), which yields the master target impedance, $z_M = z^* z_S$ = (1 [kg], 20 [N/(m/s)], 10 [N/m]). Note that these impedances indicate the scaling standard of the dynamics transformation between these manipulator systems. The operator manipulates the master arm to drive the slave arm to contact to a soft object, which is made of sponge. Figure 5(a) is the experimental results, which show the time history of position and force to the master and slave. In the figure, the positions of master and slave coincide. The force of the operational force of the master, however, is amplified twice to the force of the slave. In other word, the operational force is transferred to the slave with a scale of a half. In this case, the impedance of the object is represented in the master with an amplification of two times.

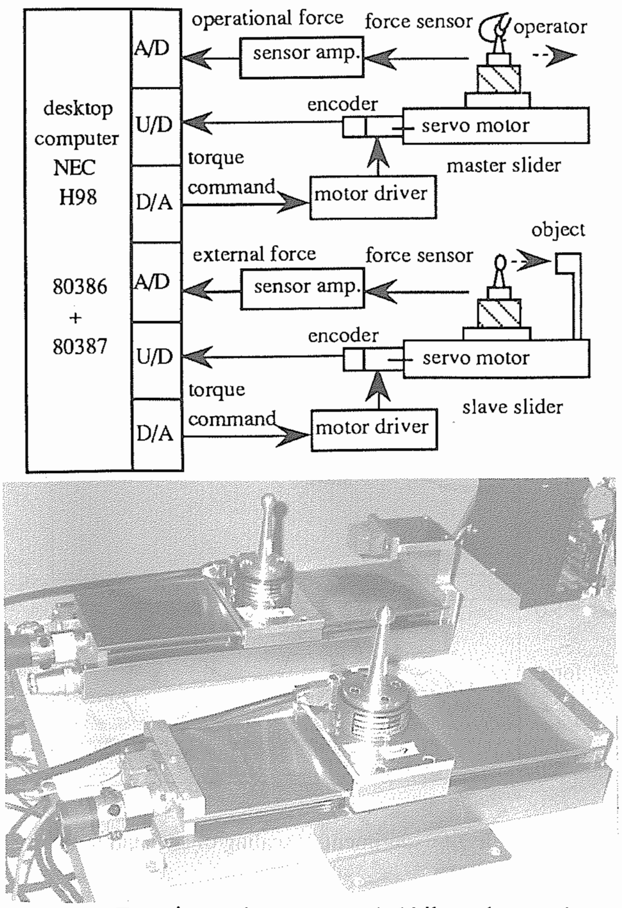


Fig.4 Experimental setup of scaled bilateral control.

2) Experiment 2: Amplification of sensation of size. According to the scaling transformation, we will derive the scaling factors. In the case of the force scaling factor, $f^* = 1$, and the size scaling factor, $l^* = 2$, then the impedance scaling factor is derived as $z^* = f^* / l^* = 0.5$. The same slave target impedance, however, yields the different master target impedance, $z_M = z^* z_S$ = (0.5 [kg], 10 [N/(m/s)], 5 [N/m]). Again, the operator manipulates the master arm to drive the slave arm to contact to the soft object. Figure 5(b) is the experimental results of the contact task. In the figure, the forces of master and slave coincide. The motion of the operator, however, is amplified twice to the motion of the slave. In other word, the slave motion is transferred to the master with a scale of two times. In this case, the impedance of the object is represented in the master with an amplification of a half.

3) Experiment 3: Amplification of sensation of size and force. In the case of the force scaling factor $f^* = 2$, and the size scaling factor $l^* = 2$, then the impedance scaling factor is derived as $z^* = f^* / l^* = 1$. For the same slave target impedance z_S, the master target impedance is derived as $z_M = z^* z_S = z_S$. Note that these impedances are now coincident. Figure 5(c) is the experimental results of the contact task to the object. In the figure, the force and position of the slave, however, is amplified with a scale of two times. In other word, the operational force and position are transferred to the slave with a scale of a half. Both position and force of the master are amplified ten times to those of the slave. Note that the object impedance to which the slave arm contacts are represented at the master system with the same scale. This is because the impedance scale factor z^*, which is determined by the force scale factor f^* and the size scale factor l^*, is equal to one in the case of $f^* = l^*$.

IV. DISCUSSION

Conventional bilateral controls have dealt with only a geometrical scale between them has been considered without any point of view of physical similarity. No regulation of arm target impedance has been considered, and no dynamics have been transformed between different scale environments. A kind of virtual real-time sensation of presence generated by a scaling transformation, should be provided for the bilateral manipulation in those environments. The proposed scaling method leads the explicit design of the target impedances of the master-slave manipulators according to physical similarity.

The experimental results show that an object in slave environment appears to the operator with amplified or minimized scales of size and force by scale transformation. It results the master system works as a virtual dynamics display with scaling "lens".

Contact stability to a rigid environment was not considered in the experiments. The contact instability may occur not only in ordinary bilateral controls but also in the scaled bilateral control. It is of course possible to improve the system to prevent the contact instability. However, the consideration of contact stability is beyond the scope of this paper. The main issue of this paper is the transformation of scaled dynamic response between different scale environments. The scaling bilateral control provides to the operator a dynamics virtually scaled environment. It is sufficient to verify the proposed method on the scaled transformation of bilateral dynamics by the simulations. The contact stability problem in those scaled bilateral controls remains for future topics.

V. CONCLUSIONS

This research presents a virtual dynamics display for teleoperation between different scale environments. The proposed master-slave system executes the similarity transformation of physical scales such as size and/or force with using impedance scaling. The virtual dynamics display provides the operator with the extended tele-existence manipulating sensation. As a results, the scaled dynamics of environment apparently appears to the operator as a virtual environment dynamics. The dynamics display will enhance the operator capability in different scale environments such as micro teleoperation or man-power amplifier.

REFERENCES

[1]E.G.Johnsen and W.R.Corliss, "Teleoperators and human augmentation," NASA, NASA-SP 5047, 1967.

[2]T.B.Sheridan, "Supervisory control:Problems, theory and experiment for application to human-computer interaction in undersea remote systems," MIT Man-Machine Systems Laboratory Report, March, 1982.

[3]D.L.Akin, M.L.Minsky et al., "Space application of automation:Robotics and machine intelligence systems (ARAMIS) - Phase II," NASA Contract Report 3734, 1983.

[4]S.Tachi and M.Abe, "Study on tele-existence(I) -- Design of visual display," Proc. SICE'82, pp.157-168, Japan, 1982.

[5]S.Tachi et al.,"Tele-existence (I) -Design and evaluation of a visual display with sensation of presence-," in Proc. 5th Symposium on Theory and Practice Robots and Manipulators (RoManSy '84), pp.245-254, CISM-IFToMM, Udine, Italy, 1984.

[6]S.Tachi and H.Arai, "Study on tele-existence (II) -Three dimensional color display with sensation of presence-,"Proc. of the '85 International Conference on Advanced Robotics(ICAR),pp.345-352,Tokyo, Japan,1985.

[7]S.Tachi, H.Arai, I.Morimoto and G.Seet, "Feasibility experiments on a mobile tele-existence system," International Symposium and Exposition on Robots (19th ISIR), Sydney, Australia, 1988.

[8]S.Tachi, H.Arai and T.Maeda, "Development of an anthropomorphic tele-existence slave robot," Proc. of International Conference on Advanced Mechatronics (ICAM), pp.385-390, Tokyo, Japan, 1988.

[9]S.Tachi, H.Arai and T.Maeda, "Tele-existence visual display for remote manipulation with a real-time sensation of presence," Proc. of the 20th International Symposium on Industrial Robots (ISIR), pp.427-434, 1989.

[10]S.Tachi and T.Sakaki,"Impedance controlled master slave system for tele-existence," Proc. of First International Symposium on Measurement and Control in Robotics, Vol.1, B.3.1.1, Houston, Texas, 1990.

[11]T.Sakaki and S.Tachi, "Impedance scaling of a tele-existence master-slave manipulation system by using similarity transformation," Proc. of Second ISMCR92, pp.295-302, Tsukuba, Japan, 1992.

[12]K.Kosuge et al.,"Control of single master multi-slave manipulator system using VIM," IEEE Proc. of Robotics and Automation, pp.1172-1177, 1990.

[13]K.Tanie, et al., "Bilateral remote control with dynamic reflection," Proc. 7th Symposium on Theory and Practice Robots and Manipulators (RoManSy '88), pp.298-308, Udine, Italy, 1988.

[14]Y.Yokokoji and T.Yoshikawa, "Control of master-slave manipulators for object teleperception," Proc. of the 5th International Symposium of Robotics Research, Tokyo, Japan, 1989.

[15]B.Hanaford,"A design framework for teleoperators with kinesthetic feedback," IEEE Trans. Rob. Autom, Vol.5, No.4, 1988.

[16]J.Dudragne et al.,"A generalized bilateral control applied to master-slave manipulators," 20th. ISIR, pp.435-442, 1989.

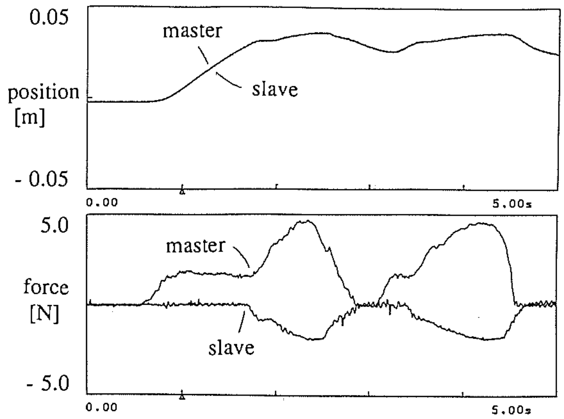
[17]R.J.Anderson and M.W.Spong, "Bilateral control of teleoperators with time delay," IEEE Trans. Automatic Control, vol.34, no.5, pp.409-501.

[18]T.B.Sheridan and Staff, "MIT research in telerobotics," Proc. of the Workshop on Space Telerobotics, vol.2, pp.403-412, JPL Publication 87-13, 1987.

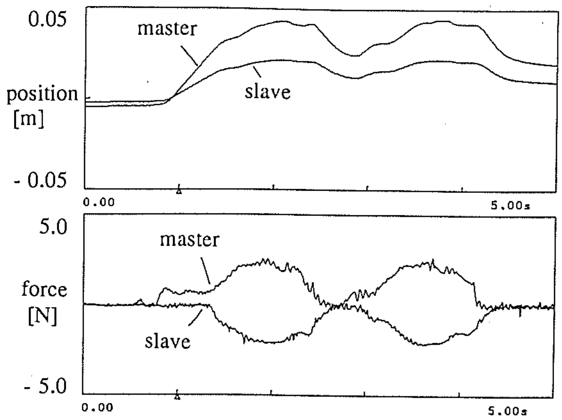
[19]J.E.Colgate,"Power and impedance scaling in bilateral manipulation," Proc. of 1991 IEEE International Conference on Robotics and Automation, Sacramento, Japan, 1991.

[20]K.Machida, Y.Toda, T.Iwata, "Graphics-simulator-augmented teleoperation system for space applications" Journal of Spacecraft and Rockets, Vol.27, No.1 pp.64-69, 1990.

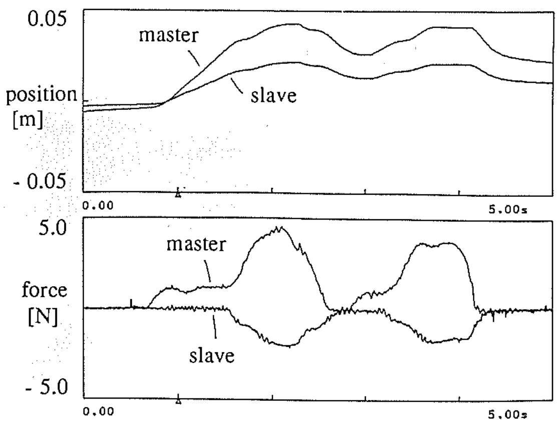
[21]R.I.Emori and D.J.Schuring, "Scale models in engineering," Pergamon Press, London, 1971.



(a) Results of experiment 1: scaling of force sensation.



(b) Results of experiment 2: scaling of size sensation.



(c) Results of experiment 3: scaling of size and force sensation.

Fig.5 Experimental results of scaled bilateral control.