THE FIRST INTERNATIONAL SYMPOSIUM ON MEASUREMENT AND CONTROL IN ROBOTICS (ISMCR '90)
GILRUTH CENTER, NASA/JOHNSON SPACE CENTER, HOUSTON, TEXAS, USA JUNE 20-22, 1990

IMPEDANCE CONTROLLED MASTER SLAVE SYSTEM FOR TELE-EXISTENCE MANIPULATION

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ABSTRACT

An impedance controlled master slave manipulation system is proposed for use as part of a tele-existence manipulation system. Tele-existence aims at the natural and efficient remote control of robots by providing a human operator at the controls with the real time sensation of presence that enables he or she to perform remote manipulation tasks dexterously with the feeling that they exist inside the slave anthropomorphic robot in the remote environment. The proposed system regulates the impedances of the master manipulator and the slave manipulator so that they coincide with each other. An impedance model of the remote environment is generated to be used for the control. Four basic impedance controlled master slave manipulation methods are proposed. It is shown that they are related to one another by some form of transformation. The impedance controlled master slave manipulation scheme is applied to the system with a time delay. The feasibility of the proposed method is demonstrated by experiments using a hardware direct drive master manipulator and a software slave manipulator.

INTRODUCTION

With the advent of science and technology it has become possible to envision teleoperation with a sensation of presence. The concept of projecting ourselves by using robots, computers and cybernetic human interfaces is called Tele-Existence, and a lot of effort has been made for the realization of this concept. This concept also provides an extension of human sensing and muscular capabilities.

Systematic research for the development of tele-existence has been conducted at MEL by feeding back rich sensory information which the remote robot has acquired to provide the operator with a real-time sensation of presence.

The principle of the tele-existence sensory display has been proposed. Its design procedure has been explicitly defined . Experimental visual display hardware has been built, and the feasibility of the visual display with the sensation of presence has been demonstrated by psychophysical experiments using the test hardware [1, 2].

A method has also been proposed to develop a mobile tele-existence system which can be remotely driven with the auditory and visual sensation of presence. A prototype mobile tele-vehicle system has been constructed and the feasibility of the method has been evaluated [3].

In order to study the use of the tele-existence system in the artificially constructed environment, the visual tele-existence simulator has been designed, a pseudo- real-time binocular solid model robot simulator has been made, and its feasibility has been experimentally evaluated [4].

An anthropomorphic robot mechanism with an arm having seven degrees of freedom has been designed and developed as a slave robot for feasibility experiments of teleoperation using the tele-existence method (Fig. 1). A head mounted display and a head linked display (Fig. 2) with a sensation of presence have also been designed and developed as the display sub-system for the master [5, 6]. By using this tele-existence master slave manipulation system, the feasibility of the tele-existence system has been demonstrated.

However, the natural feedback method of kinesthetic information for tele-existence has not been established. The conventional force feedback master slave manipulation method cannot design the dynamics of the system as desired and cannot be extended to the situation with a very long time delay. Although several works have been conducted for the improvement of the master slave manipulation system (MSMS) [7,8], no unified design scheme for tele-existence has been established.

It has been pointed out by N. Hogan [9] that the system design using the concept of mechanical impedance leads to a flexible and unified design of the manipulation system. Recently the use of impedance control has been considered, and analysis has been made by using the two port network theory [10,11,12].

In this paper, an impedance controlled master slave manipulation method is proposed for use in tele-existence. Four basic schemes are presented. It is shown that they are related to one another by some form of transformation. The impedance controlled master slave manipulation scheme is applied to the system with a time delay. The feasibility of the proposed method is demonstrated by experiments using a hardware direct drive master manipulator and a software slave manipulator.

CONTROL PRINCIPLE

Two important characteristics that MSMS for tele-existence must satisfy are:

(1) The dynamics of the MSMS can be designed arbitrarily and can be regulated arbitrarily to ensure the known realistic feeling. Although it is ideal for tele-existence that both the position and force responses of the master and slave manipulators are exactly equal regardless of the object dynamics, it is physically unrealizable because this condition requires the complete elimination of the master and slave manipulator dynamics, which means that the total dynamic characteristic must be zero, including zero mass. The conventional force feedback type MSMS tried to reduce the dynamics of the master and slave manipulators as much as possible, but it could not assign an arbitrary known dynamic to the MSMS. It is necessary for tele-existence MSMS to be able to choose and design known dynamics arbitrarily.

(2) The amount of information exchanged between the master and slave systems should be as small as possible. This condition is important especially in the implementation of a real system.

The proposed method solves the above problems as follows:

Before building a master slave system, the dynamic characteristics of the master and slave manipulators are controlled locally so that they have exactly the same dynamic characteristics. This can be attained for instance by controlling both manipulators by the impedance control method [13].

The equation of motion of a manipulator to be controlled to the desired impedance (M0, B0, K0), which is represented in equation (2), is given as follows:

$$I\ddot{\theta} + Dv\dot{\theta} = Ta + J^T Fe \qquad (1)$$

, where I and Dv are the inertia and viscosity matrices of the manipulator, respectively. Ta, Fe and θ are the actuator output torque, external torque and rotational angle vectors, respectively, and J^T denotes the transpose of the Jacobian.

$$Z(s) = M0\, s + B0 + (1/s)\, K0 \qquad (2)$$

By applying the torque represented in equation (4), the desired impedance of (2) is realized and the apparent system equation becomes as follows:

$$Fe = M0\,(\ddot{X}-\ddot{X}0) + B0\,(\dot{X}-\dot{X}0) + K0\,(X-X0) \qquad (3)$$

, where $\{\ddot{X}0, \dot{X}0, X0\}$ is a target motion of the manipulator.

$$Ta = (I-J^T M0\, J)\ddot{\theta} + (Dv - J^T M0\, \dot{J} - J^T B0\, J)\dot{\theta} + J^T\{M0\, \ddot{X} + B0\, \dot{X} + K0(X0 - L(\theta))\} \qquad (4)$$

, where $X = L(\theta)$.

Either force information or motion (acceleration, velocity and position) information is transmitted from the master to the slave, and vice versa.

The proposed impedance controlled MSMS can be classified into four basic types according to the types of information exchanged between the master and slave:

In the Dual Force Transmission Method (D-F), the master manipulator transmits the human master's operational force to the slave manipulator while the slave transmits the reaction force from the environment to the master manipulator. The Motion Force Transmission Type (M-F) transmits the master's motion to the slave, and the force from the slave to the master. In the Force Motion Transmission Type (F-M), the master's force and the slave's motion are exchanged. The Dual Motion Type (D-M) exchanges motions of both the master and slave.

Under the above condition, the equation of motion of the master manipulator and the master slave control strategy can be described as follows:

$$F0 = M0\,\ddot{X}m + B0\,\dot{X}m + K0\,Xm - F1 \quad (5)$$

$$F1 = C1 \quad (6)$$

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

$$F2 = M0\,\ddot{X}s + B0\,\dot{X}s + K0\,Xs + Fe \quad (7)$$

$$F2 = C2 \quad (8)$$

The equation of motion of an object can be described as follows:

$$Fe = M\,\ddot{X}s + B\,\dot{X}s + K\,\delta Xs \quad (9)$$

, where M0, B0, and K0 are 6x6 inertia, viscosity, and stiffness matrices of the master (i.e. slave) manipulator, respectively. (This triad of M, B and K will be called the mechanical impedance parameters of the system.) M, B, and K indicate the mechanical impedance parameters of the object. F0 denotes the force exerted by the human operator (human master), F1 is a 6x1 inner force vector of the master manipulator, F2 is that of the slave manipulator, and Fe indicates the reflection force vector from the object. Xm and Xs denote the position vectors of the master and the slave, respectively, and δXs is the position deviation vector of the object.

The choice of C1 and C2 determine the types of the impedance controlled master slave schemes as follows:

(1) In the D-F Type, C1 and C2 are set as follows (see Fig. 3a):

$$C1 = -Fe \quad (10)$$

$$C2 = F0 \quad (11)$$

By use of this control, the positional error, i.e., e = Xm - Xs, can be represented by the equation (1). The error can be reduced to zero by appropriately selecting the mechanical impedance parameters (M0, B0, K0), and Xm becomes equal to Xs, which can be described as X.

$$M0\,\ddot{e} + B0\,\dot{e} + K0\,e = 0 \quad (12)$$

In this system the relation between the operational force and the reaction force becomes as follows:

$$F0 = (M0\,\ddot{X} + B0\,\dot{X} + K0\,X) + Fe \quad (13)$$

If we select an appropriately small and known impedance, F0 becomes very similar to Fe, and the operator can feel the object as closely as in direct manipulation while knowing the exact residual dynamics (ideal for tele-existence).

The residual impedance can be selected for instance to satisfy the critical damping condition of the equation (14) to ensure stability.

$$(M0^{-1}\,B0)^2 - 4\,M0^{-1}\,K0 = 0 \quad (14)$$

$$\det\{ sI + (1/2)\,M0^{-1}\,B0 \} = 0 \quad (15)$$

A norm of the impedance is defined as follows:

$$N[Z(s)] = \sqrt{tr\,[\,z(s)^T\,Z(s)\,]} \quad (16)$$

This has the relation of (17).

$$N[Z(s)] = |1/s|\,N[M0]\,N[T]^2\,N[T^{-1}]^2 \times \{(s - \lambda 1)^2 + \quad + (s - \lambda 6)^2\} \quad (17)$$

(2) The M-F type can be attained by setting C1 and C2 as follows (see Fig. 3b):

$$C1 = -Fe \quad (18)$$

$$C2 = M0\,\ddot{X}m + B0\,\dot{X}m + K0\,Xm \quad (19)$$

The relation between the operational force and the reaction force is described by equation (20), or by (21) and (22).

$$F_O = (M_O \ddot{X}_m + B_O \dot{X}_m + K_O X_m) + F_e \quad (20)$$

$$\text{or, } F_O = (M_O \ddot{X}_m + B_O \dot{X}_m + K_O X_m) + (M_O \ddot{e} + B_O \dot{e} + K_O e) \quad (21)$$

$$F_e = M_O \ddot{e} + B_O \dot{e} + K_O e \quad (22)$$

(3) The F-M Type can be realized by applying the following C1 and C2 (see Fig. 3c):

$$C_1 = M_O \ddot{X}_s + B_O \dot{X}_s + K_O X_s \quad (23)$$

$$C_2 = F_O \quad (24)$$

The relation between the operational force and the reaction force becomes as follows:

$$F_O = M_O \ddot{e} + B_O \dot{e} + K_O e \quad (25)$$

$$F_e = (M_O \ddot{e} + B_O \dot{e} + K_O e) - (M_O \ddot{X}_s + B_O \dot{X}_s + K_O X_s) \quad (26)$$

(4) In the D-M type, C1 and C2 are set as follows (see Fig. 3d):

$$C_1 = M_O \ddot{X}_s + B_O \dot{X}_s + K_O X_s \quad (27)$$

$$C_2 = M_O \ddot{X}_m + B_O \dot{X}_m + K_O X_m \quad (28)$$

The relation between the operational force and the reaction force is as follows:

$$F_O = F_e = M_O \ddot{e} + B_O \dot{e} + k_O e \quad (29)$$

CONTROL SCHEME TRANSFORMATION

The M-F scheme can be transformed to the D-F scheme by estimating the force Fe [13] and by changing the equation (19) to (30).

$$C_2 = M_O \dot{X}_m + B_O \dot{X}_m + K_O X_m + F_e \quad (30)$$

Similarly the F-M scheme can be transformed to the D-F scheme by estimating the force Fo and using equation (23) instead of (31).

$$C_1 = M_O \ddot{X}_s + B_O \dot{X}_s + K_O X_s - F_O \quad (31)$$

The D-M scheme can be transformed to either M-F or F-M, but can not be transformed to D-F. However, by using a model of the environment and an object, it becomes equivalent to D-F.

The relations among the impedance controlled MSMS are shown in Fig. 4.

MODEL BASED IMPEDANCE CONTROLLED MSMS

When we think of the use of tele-existence under a situation where the master and the slave are far apart, perhaps on different planets, it is quite effective to use a realistic model of the environment, including objects and robots, i.e., the use of virtual environments.

Figure 5 shows the concept of a model based impedance controlled MSMS using a virtual environment, and Fig. 6(a) shows an example of the system arrangement based on the D-F method (the other three types can also be used). A human operator works with the master manipulator with force feedback from the model in a virtual environment, which is represented by a mechanical impedance model. 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:

$$Z(X) = [z_{p1}, z_{p2}, z_{p3}, z_{r1}, z_{r2}, z_{r3}] \quad (32)$$

The same model is provided at the slave side. The transmitted information of the master's motion or operational force is applied to both the model and the real slave manipulator, and the responses of them are monitored. The motion of the slave arm model and the real slave are compared, and when the error exceeds a certain limit, the system stops, and the caution signal is sent to the operator with the information regarding when and under what condition it stopped. It will then come back to the environment identification phase again. After reidentification, the operator backs up and starts his task through the virtual environment from the point where the system failed. This flow is shown in Fig. 6(b).

It is possible to add a demon like mechanism, which always identifies the environment and modifies and/or adds to the model independent of the master slave operation.

EXPERIMENTAL RESULTS

The direct drive manipulator with three degrees of freedom, a precise mathematical model of which had been acquired [13], was used as a master manipulator (see Fig. 7). Each joint of the manipulator was driven by a direct drive DC motor (Inland) and an encoder of 2,000 P/R with a four-times frequency multiplier, which was applied to an up-down counter to estimate 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 used as the estimated value of the angular velocity. The drawback of a direct application of this method would be that the last estimated value would continue to be output when the motor stopped or rotated at a very low speed. In order to solve this problem, the last estimated value was reduced exponentially when no pulse was measured at each sampling time [5]. Digital low pass filters estimated the angular velocity and the angular acceleration. A microprocessor (Intel 80386 20 MHz with 387 coprocessor) calculated the necessary torque to attain the desired impedance, outputs of which were applied to servo-amps to control the manipulator. The mechanical impedances of the two degrees of freedom of the manipulator (x and y directions) were controlled in the experiment. A program was written in the C language and the cycle time was less than 3 ms.

The slave manipulator and the object were simulated by the dynamic model in the computer (Intel 80386 20 MHz with 387 coprocessor). Impedances were assigned for the master manipulator, slave manipulator and the object. Models of the manipulators and the object were given in the computer. A human subject operator operated the master manipulator, and dynamic responses of the master and slave manipulators were measured under several operation schemes.

Figure 8(a) shows the results for the conventional force feedback type MSMS, and Fig. 8(b) shows the results for the D-F type impedance controlled MSMS. As for the force feedback type MSMS, the following scheme was used:

$$F0 = Mm\ \ddot{X}m + Bm\ \dot{X}m + F1 \tag{33}$$

$$F1 = Kf\ (Fe - F0) \tag{34}$$

$$F2 = Ms\ \ddot{X}s + Bs\ \dot{X}s + Ks\ Xs + Fe \tag{35}$$

$$F2 = Kv\ (\dot{X}m - \dot{X}s) + Kp\ (Xm - Xs) \tag{36}$$

$$Fe = M\ \ddot{X}s + B\ \dot{X}s + K\ \delta Xs \tag{37}$$

, where the force, velocity and position feedback gains (Kf, Kv and Kp) were set 2, 10 and 1000, respectively.

In this system, the reflection force which the operator felt was:

$$F0 = (1 + Kf)^{-1}(M0\ \ddot{X} + B0\ \dot{X}) + (1 + Kf)^{-1}Kf\ Fe \tag{38}$$

M, B and K were set to 0.2 [kg], 0 [N/(m/s)] and 10.0 [N/m], respectively.

For the D-F impedance controlled MSMS, the following parameters were used:

M0 = 0.05 [kg], B0 = 0.4 [N/(m/s)] and K0 = 0.9 [N/m].

The results showed that the D-F impedance controlled MSMS system had a better force response than the conventional force feedback MSMS.

Figure 8 (c) shows the results of the model based impedance controlled MSMS. In this experiment, the D-M type was used with a time delay of 0.5 [s]. The slave manipulator exactly followed the master with a time delay of 0.5 [s], while the reaction force from the model was fed back to the operator without time delay.

Similar results were obtained for the systems with a time delay of 5.0 [s] and 50.0 [s].

CONCLUSION

Use of the impedance controlled master slave manipulation system has the following advantages and can be implemented in a tele-existence manipulation system.

1) Arbitrary design of residual dynamics of the system becomes possible. An operator can choose not only the system optimized for the average operator but also the system which has dynamics that best fits him or her.

2) The amount of information transmitted between the master and the slave is relatively small.

3) Since the MSMS with known dynamics can be realized, introduction of an environmental model and the use of a virtual model are quite straight forward.

4) The dynamics of manipulators, objects and environments are all described in terms of the mechanical impedance. Therefore the control principle and its notation become quite simple and easy to implement.

5) The use of the object and environment model leads to the MSMS system that is effective for a system with a very long time delay.

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FIGURES

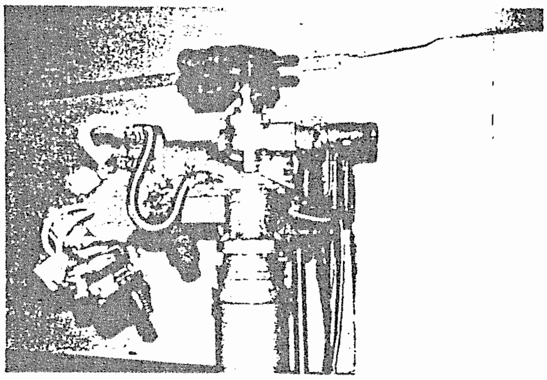

Fig. 1 Anthropomorphic slave robot used for tele-existence.

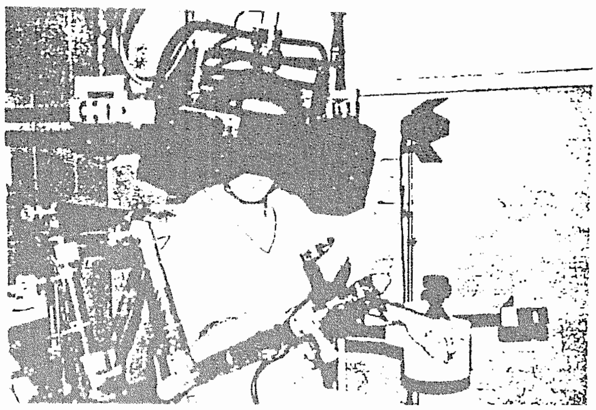

Fig. 2 Tele-existence master system having a head-linked visual and auditory display with a sensation of presence.

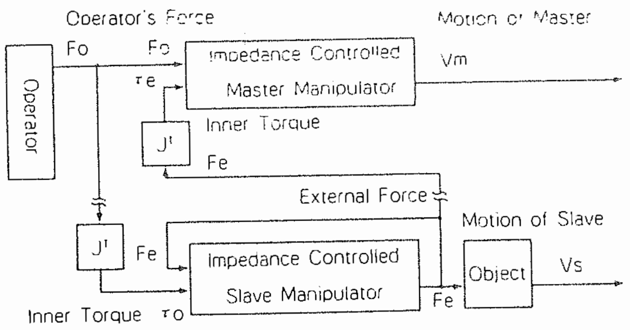

Fig. 3 (a) D-F type impedance controlled MSMS.

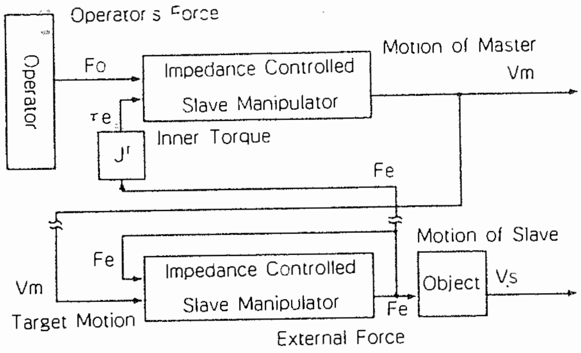

Fig. 3 (b) M-F type impedance controlled MSMS.

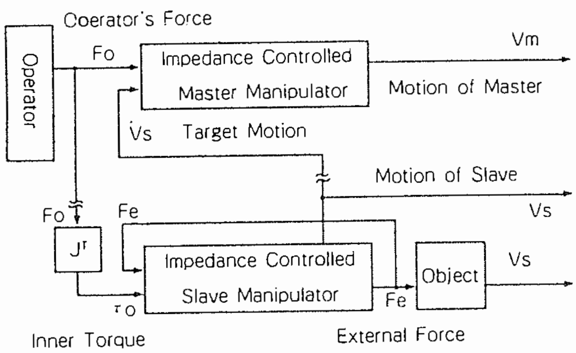

Fig. 3 (c) F-M type impedance controlled MSMS.

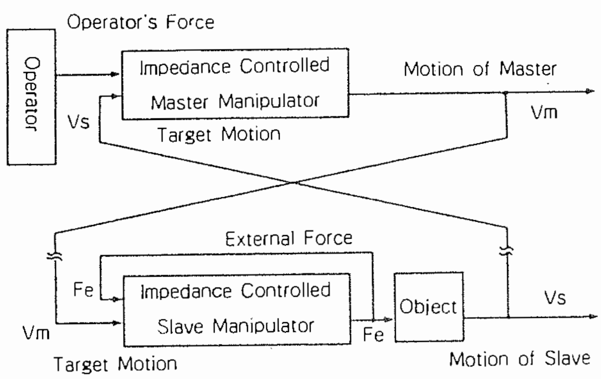

Fig. 3 (d) D-M type impedance controlled MSMS.

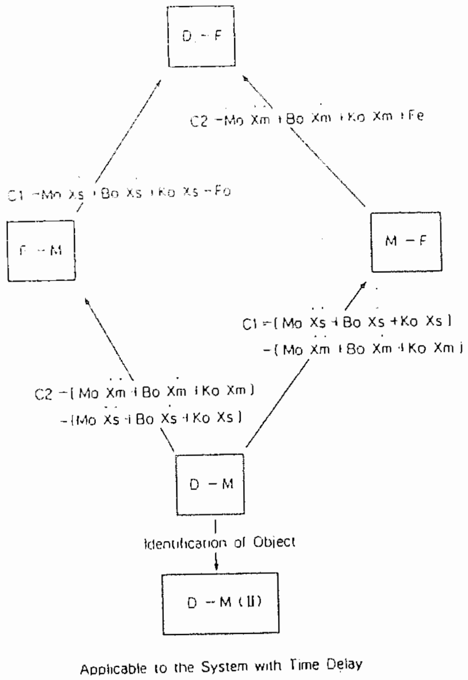

Fig. 4 Transformational relations among the impedance controlled MSMSs.

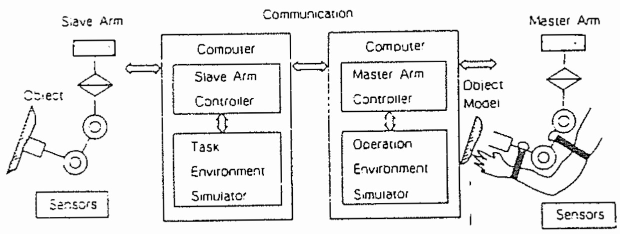

Fig. 5 Schematic diagram of the model based MSMS.

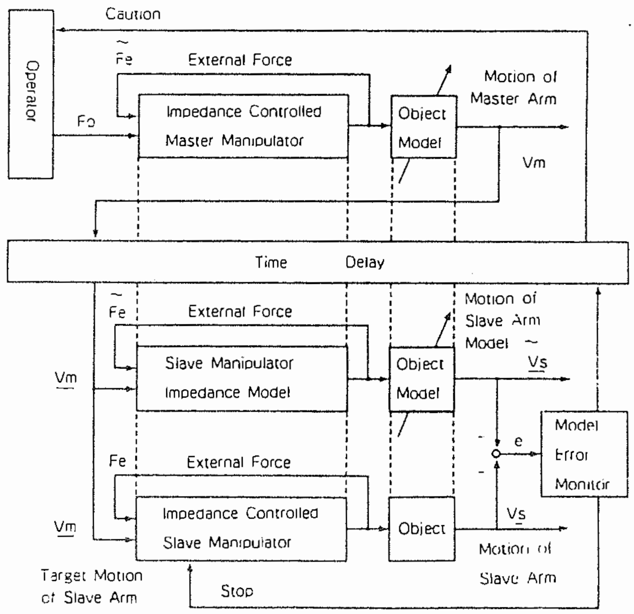

Fig. 6 (a) Implementation of the model based MSMS using the D-M impedance control scheme.

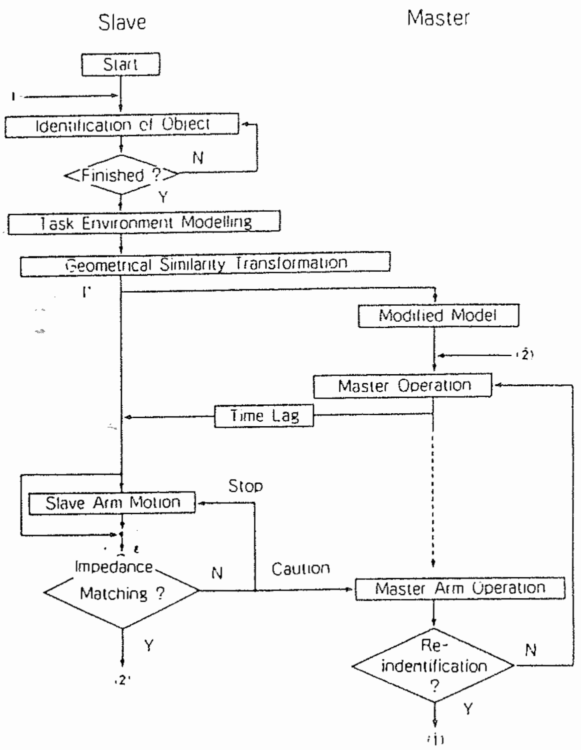

Fig. 6 (b) Flow chart of the operation.

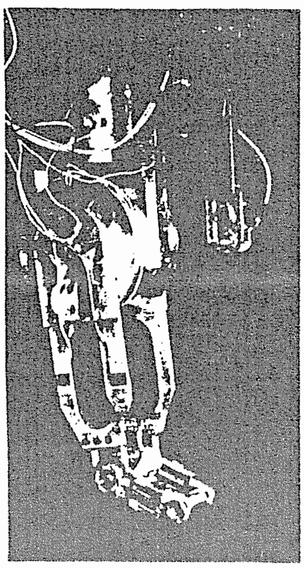

Fig. 7 Direct drive manipulator used for the master.

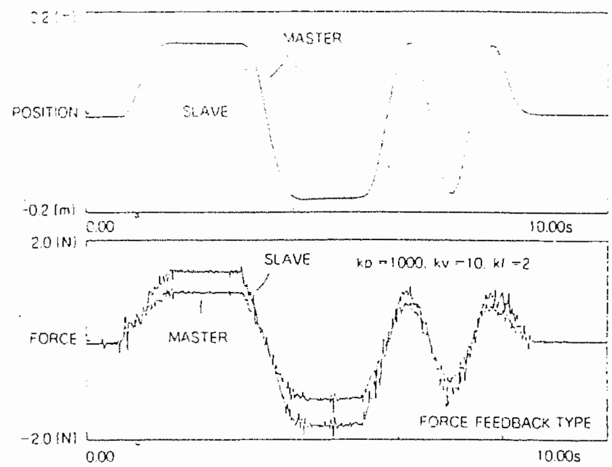

Fig. 8 (a) Results for the conventional force feedback scheme.

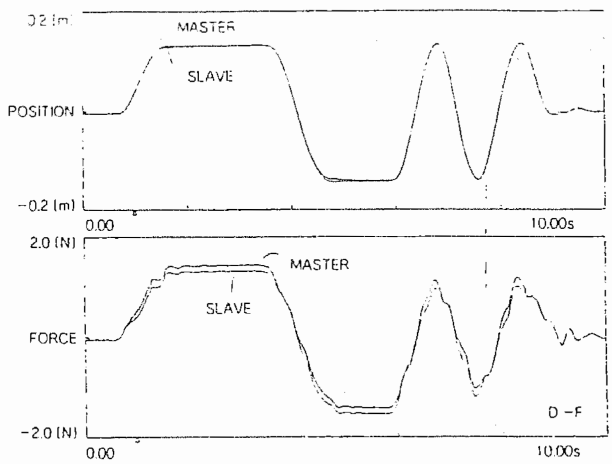

Fig. 8 (b) Results for the D-F type impedance controlled MSMS.

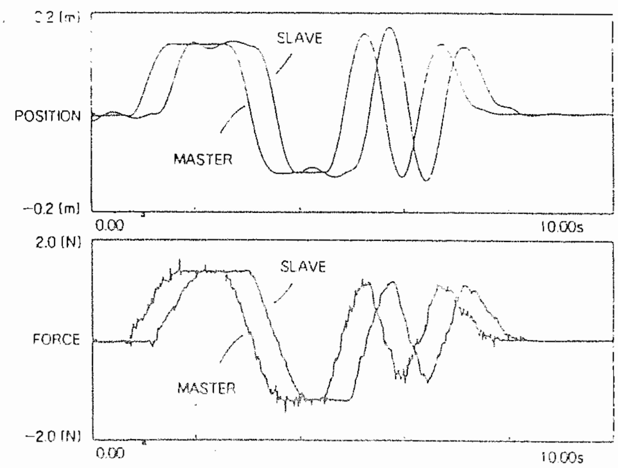

Fig. 8 (c) Results for the system with a time delay of 0.5 [s].