MASTER–SLAVE SYSTEM WITH FORCE FEEDBACK BASED ON DYNAMICS OF VIRTUAL MODEL

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Abstract

A master-slave system can extend manipulating and sensing capability of a human operator to separated environment from him or her. But the master-slave system has the two serious problems: one is the mechanically large impedance of the system, the other is mechanical complexity of the slave for complex remote tasks. These two problems reduce the efficiency of the remote task through the master-slave system.

If the slave has local intelligence, the slave can help the human operator by using its good points like fast calculation and large memory. After the authors suppose that the slave is the dextrous hand with many degrees-of-freedom (DOF) and it manipulates the object with known shape, it is suggest that the dimensions of the remote work space should be shared by the human operator with the slave.

The effect of the large impedance of the system can be reduced the virtual model, which is a physical model constructed in a computer and has physical parameters as if it was in real world. The way to determine the damping parameter dynamically of the virtual model in one DOF master-slave system is proposed. The experimental result shows that this virtual model is better than the virtual model with fixed damping.
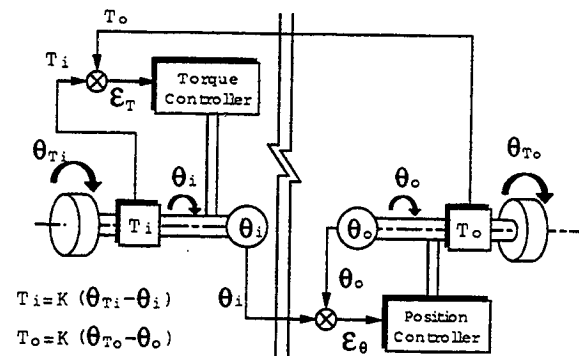
Figure 1: Traditional bilateral master-slave system : position and force control.
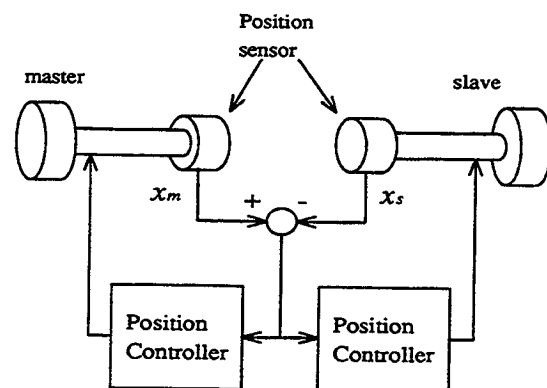
Figure 2: Traditional bilateral master-slave system : position and position control.

1 Introduction

Traditional master-slave systems began in 1940's as a teleoperator through which the human operator could handle the radioactive materials while he or she was separated from that material physically. The traditional master-slave system consisted of the two system, the master arm, and the slave arm [1], [2]. The two systems are connected each other directly by a servo mechanism, called bilateral servo (Figure 1, 2). These

traditional systems had two problems:

1. The human operator felt the dynamics of the system in addition to that of the remote environment. Because master-slave systems have mechanically large impedance, the human operator and the remote environment in the system cannot actuate each other accurately.

2. The master arm had the same form as the slave has. When the slave has many degrees-of-freedom (DOF) to perform the remote task dextrously, the human operator must control all the DOF dextrously. This system also needed the wide bandwidth telecommunication between the master and the slave.

The work [3] coped with the first problem, putting an impedance matrix, which changes the impedance of master-slave systems arbitrary, between master and slave. Furuta *et al.* [7] propose the Virtual Internal Model Following Control in order to change dynamics of master slave systems. The discussion in [4] shows *Supervisory Control*, the way to avoid the second problem.

In order to cope with the second problem, this paper suggest that the human operator shares the dimensions of the remote work space with the master-slave system. The authors include the virtual model with physical parameters into the system.

The authors also propose to determine the physical parameters of the virtual model dynamically, and show the way to determine the damping parameter of the virtual model, which stabilize the one DOF master-slave system. The advantage of this parameter determination are shown through one DOF master-slave experiments.

2 Master-Slave System with Virtual Model

In the systems showed in Figure 1 and 2, The master make its position (or torque) coincide with position (or torque) of the slave by this mechanism, and the slave also make its position (or torque) coincide with the position (or torque) of the master by the same mechanism.

These systems have a serious problem. The two systems have mechanically large impedance because the master must actuate a human operator and the slave must produce strong force like human beings to carry out some tasks in a remote environment instead of the operator. Measured force or motion in master and
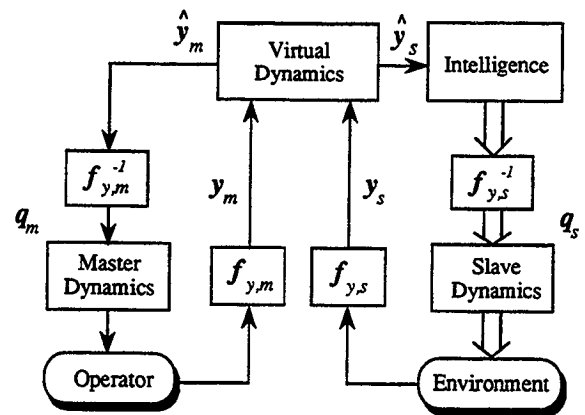

Figure 3: Master slave system with virtual model.

slave system involves this large impedance of the one system or both [4]. These master-slave system cannot accurately communicate force and motion information each other.

The human operator must feel the force information from the remote environment through the systems in order to perform a remote task as if he or she was in the environment. But that impedance reduces reality about force feeling and makes the remote task inefficient.

The authors include the virtual model in order to change the dynamics of the master-slave system (Figure 3). The virtual model connects the master and slave: it gives the position (or force) reference to these systems while it is given the force (or position) inputs for calculation of its position (or force) by them. The parameters of the virtual model are chosen as they reform the system and keep the stability of it.

3 Dextrous Slave Manipulator

In this section, the authors apply the virtual model to a master-slave system which consists of a dextrous slave manipulator and a master which has less DOF than the slave.

The dextrous slave manipulator is useful to make it perform tasks in remote environment by itself because of its large DOF. This slave can be controlled by a master manipulator with the same form as the slave has. In this case, a human operator of this master-slave system controls all the DOF of the slave by controlling the master. The more DOF the slave and master has, the more they become mechanically heavy, large and uncontrollable for human beings.
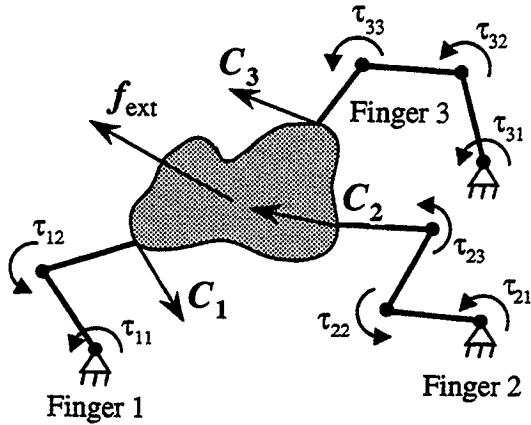
Figure 4: Object grasped by 3 fingers.

If the slave manipulator has a certain intelligence, the human operator and the slave can share dimensions of remote work space, and the slave can be controlled by a master with less DOF than the master.

For example, when the dextrous slave manipulator rotates a valve in a pipeline by grasping, the slave can possess shape and material information of the valve and use a computer as the intelligence. This intelligent slave manipulator makes up for some parts of dimensions of the remote work space, because the slave can autonomously keep a sufficiently grasping force to rotate the valve and vary its configuration with the rotational angle of the grasped valve. The human operator governs only one dimension about the rotation around the center of the valve directly. He or she does not need any feedback information except that of this dimension in order to control the slave and feel the reality of the remote task. Then the master manipulator can reduce its DOF in proportion to work of the slave intelligence.

The dextrous and intelligent slave manipulator reduces the DOF of the master, but dimensions for which the slave can make up change according to remote tasks. A controller of higher level must determine what dimensions the slave can handle autonomously. This section supposes that these dimensions are known.

3.1 Dextrous Manipulation

When m fingers grasp an object with known shape(Figure 4), an external force added to the object and contact forces of the finger tips are related as

$$f_{ext} = Wc \qquad (1)$$

where $f_{ext} \in \mathbb{R}^6$ is the generalized force vector

$$f_{ext} = [f_x, f_y, f_z, m_x, m_y, m_z]^T = \begin{bmatrix} f \\ m \end{bmatrix} \qquad (2)$$

and $c \in \mathbb{R}^n$ means the contact force vector of the finger tips. The elements of c use *Wrench Representation* [5]. In this representation, each particular type of contact— point contact or soft finger contact, a contact with friction or without, etc. [5]—has a fixed coordinate. The wrench representation treats forces and moments, which are scalar intensities along an axis of the coordinate, as general entity, the *wrench*. n depends on the type and the number of the contact.

The matrix $W \in \mathbb{R}^{6 \times n}$ contains the n contact wrench directions in its column. The size, magnitude and rank of the matrix W can vary with changes of the type, variation of the direction and displacement of the position of the contacts. We always assume rank$(W) = 6$.

The stable grasping needs internal force, which is made by some wrenches exerted by the fingers in addition to minimum degrees of freedom to determine the position and orientation of the object. c must have n dimensions which is grater than six to produce the internal force. It can be split as

$$c = c_p + c_h \qquad (3)$$

where c_p is particular solution of the equation (1) and c_h is homogeneous solution of it:

$$Wc_h = 0 \qquad (4)$$

The equation (1) has a nontrivial solution because of $n > 6$ and rank$(W) = 6$. The authors choose c_p,

$$c_p = W^+ f_{ext} \qquad (5)$$

as the solution. W^+ is the generalized inverse matrix of W and given as

$$W^+ = W^T [WW^T]^{-1} \qquad (6)$$

The authors include the linear mapping N to define the internal force vector explicitly [6].

Definition 1 *The matrix $N \in \mathbb{R}^{n \times (n-6)}$ contains the orthonormal basis vectors $c_{i,h}$ in its columns, which span the $(n - 6)$ dimensional null space of W.*

$$N = [c_{1,h}, c_{2,h}, \ldots, c_{n-6,h}] \qquad (7)$$

N is the linear mapping from f_{ext} in the coordinates of the object to the c_h in the coordinates of the wrench system:

$$c_h = N f_{int} \qquad (8)$$

$$f_{int} = N^T c_h \qquad (9)$$

The two equations, (1) and (8) can be written into one equation [5].

$$\mathcal{F} = (G^T)^{-1} c \qquad (10)$$

$$c = G^T \mathcal{F} \qquad (11)$$

A generalized force vector $\mathcal{F} \in \mathbb{R}^n$ is defined as

$$\mathcal{F} = \begin{bmatrix} f_{ext} \\ f_{int} \end{bmatrix} \qquad (12)$$

The regular matrix $G \in \mathbb{R}^{n \times n}$ is called the grip matrix, or the grip transform matrix, and is written with W in (1) and N in (8):

$$[G^T]^{-1} = \begin{bmatrix} W \\ --- \\ c_{1,h}^T \\ \vdots \\ c_{n-6,h}^T \end{bmatrix} = \begin{bmatrix} W \\ --- \\ N^T \end{bmatrix} \qquad (13)$$

Using this grip transform matrix G, the object external and internal velocities v_{ext} and v_{int} are related to the contact point velocity $d \in \mathbb{R}^n$, which is represented by *Twist Representation* and uses the same coordinates as the wrench representation does [5].

$$d = G^{-1} \mathcal{V} \qquad (14)$$

$$\mathcal{V} = G d \qquad (15)$$

where

$$\mathcal{V} = \begin{bmatrix} v_{ext} \\ v_{int} \end{bmatrix}, \qquad (16)$$

$$v_{ext} = [v_x, v_y, v_z, \omega_x, \omega_y, \omega_z] = \begin{bmatrix} v \\ \omega \end{bmatrix} \qquad (17)$$

and $v_{int} \in \mathbb{R}^{n-6}$ is the vector of internal velocity deforming the object body. The equations (14) and (15) can be rewritten ([6]) with the definition (13) as

$$d = \begin{bmatrix} W^T & N \end{bmatrix} \mathcal{V} \qquad (18)$$

$$\mathcal{V} = \begin{bmatrix} [W^T]^+ \\ N^T \end{bmatrix} d \qquad (19)$$

3.2 Force Feedback to Master

In the subsection 3.1, the external force, internal force, external velocity and internal velocity of the grasped object are related to the force and velocity of the finger tips by the grip transform matrix. This subsection shows how to make the force feedback between the slave manipulator described in the subsection 3.1 and

a master which has less DOF, one degree of freedom, than the slave has.

The virtual model lies in its own space constructed in a computer and has the scalar position $p_v \in \mathbb{R}$. The authors give a physical dynamics to the virtual model as

$$M_v \ddot{p}_v + D_v \dot{p}_v + K_v p_v = F_m + F_s \qquad (20)$$

where M_v, D_v and $K_v \in \mathbb{R}$ correspond to the inertia, damping and stiffness parameter, respectively, about the position p_v, and they can be chosen arbitrary. F_m, $F_s \in \mathbb{R}$ are the generalized forces exerted to the master by the human operator and to the slave by the remote environment, respectively. If p_v means the angular position, F_m and F_s mean the torque.

The authors define the control problem of the master-slave system as described below.

Definition 2 *The position error of master $e_{p,m}(t) \in \mathbb{R}$ is defined as*

$$e_{p,m}(t) = p_m^d(t) - p_m(t) \qquad (21)$$

where the scalar $p_m^d \in \mathbb{R}$ is the desired master position and $p_m(t) \in \mathbb{R}$ is the real master position. These positions correspond to the dimension which the human operator wants to control directly with force feeling in the dimensions of the object position.

Definition 3 *The position error of the slave manipulator, $e_{p,s} \in \mathbb{R}^6$, is defined with the position of the grasped object as*

$$e_{p,s}(t) = p_s^d(t) - p_s(t) \qquad (22)$$

where $p_s(t) \in \mathbb{R}^6$ is the position of the grasped object, and $p_s^d(t) \in \mathbb{R}^6$ is the desired position.

$$p_s^d(t) = \begin{bmatrix} r_s^d(t) \\ \varphi_s^d(t) \end{bmatrix}, \quad p_s(t) = \begin{bmatrix} r_s(t) \\ \varphi_s(t) \end{bmatrix} \qquad (23)$$

$r_s \in \mathbb{R}^3$ *designates the vector from the coordinates origin to the center of mass of the object.* $\varphi \in \mathbb{R}^3$ *represents the roll-pitch-yaw orientation of the object frame of which the coordinates are the principal axis of inertia.*

The slave manipulator must exert some internal forces on the object in order to grasp it stably. The necessary internal forces can be calculated from some information: the coefficients of friction of the object surface, the weight of it, etc. We suppose that the magnitude and the orientations of this internal forces are given.

Definition 4 *We define the internal grasp force error of the slave $e_{f,s}$, using the wrench intensity vector c_h included in the subsection 3.1.*

$$e_{f,s}(t) = c_h^d(t) - c_h(t) \tag{24}$$

where the vector c_h^d contains the wrench intensities, which make the desired internal force, in its elements.

Definition 5 *The desired positions given to the master and slave are proportion to the position of the virtual model (20).*

$$p_m^d(t) = k_m p_v(t) \tag{25}$$

$$p_{s,i}^d(t) = \begin{cases} k_s p_v(t) & (i = l) \\ p_{s,i}(0) & (i \neq l) \end{cases} \tag{26}$$

where $p_{s,i}^d \in \mathbb{R}$ and $p_{s,i} \in \mathbb{R}$ means the ith element of the vector p_s^d and p_s, respectively. Only the lth element of p_s^d varies in proportion to p_v, while another element is given an initial value of $p_s(t)$ element. $k_m \in \mathbb{R}$ and $k_s \in \mathbb{R}$ are proportional coefficients about position.

$p_v(t)$ is calculated from the equation (20), while the external forces added on the virtual model, $F_m(t)$ and $F_s(t)$, is measured by the master and the slave system. As the scalar position of the virtual model is given to the only lth element of the desired position vector of the slave, the only lth element of the measured external force vector of the slave f_{ext} is used as the scalar force of the slave in the equation (20):

$$F_s(t) = f_{ext,l} \tag{27}$$

$f_{ext,l} \in \mathbb{R}$ is the lth element of f_{ext}.

Therefore, this virtual model gives the position tracking and the force feedback to the master-slave system about the only one dimension which corresponds to the lth element of p_s and f_{ext}.

Definition 6 (Control Goal) *The goal of the control algorithms in the master-slave system is to assure the position error of master $e_m(t)$, that of slave $e_s(t)$ and the internal grasp force error $e_{f,s}$ to become zero.*

$$e_{p,m}(t \to \infty) \to 0 \tag{28}$$

$$e_{p,s}(t \to \infty) \to 0 \tag{29}$$

$$e_{f,s}(t \to \infty) \to 0 \tag{30}$$

The master and slave system with the mechanically inherent impedances make their position coincide with the position of the virtual model. The dynamics of the virtual model becomes predominant in the mechanical dynamics of this master-slave system, because the position of the virtual model is determined with the measured forces on the two system by calculation.

3.3 Local Control of Slave and Master

The slave manipulator described in the subsection 3.1 can be controlled with the computed torque method for the grasped object to have the impedance [6],

$$f = K_m \delta\ddot{p} + K_d \delta\dot{p} + K_s \delta p \tag{31}$$

where the matrices K_m, K_d, $K_s \in \mathbb{R}^{6 \times 6}$ are the impedance inertia, damping and stiffness parameters. $f \in \mathbb{R}^6$ is the resulting generalized force imposed on the center of mass of the grasped object. $\delta p \in \mathbb{R}^6$ is displacement of the position and orientation vector $p \in \mathbb{R}^6$ like the vector defined in (23). We suppose this equation (31) is always asymptotically stable as

$$\delta p(t \to \infty) \to 0 \tag{32}$$

when $f = 0$.

The master can be controlled more easily than the slave. When the master has the dynamics as

$$M_m \ddot{p}_m + D_m \dot{p}_m = \tau_m + F_m \tag{33}$$

where M_m, $D_m \in \mathbb{R}$ are the inertia and damping parameter of the master. F_m and $\tau_m \in \mathbb{R}$ are the external force exerted to the master and the force produced by the master. We can control the position of this system to realize the goal (28) by the τ_m,

$$\tau_m = K(p_m^d - p_m). \tag{34}$$

4 Physical Parameter of Virtual Model

As mentioned earlier, the traditional master-slave system can not communicate the force information between the human operator and the remote environment because of the mechanically large impedance of the system. The subsection 3.2 describes that the dynamics of the system can be changed when the system includes the virtual model. If the system uses the virtual model with smaller impedance than the master and slave has, the impedance of the systems becomes smaller than that of the traditional system.

The paper [7] showed that the master-slave system which consists of a virtual internal model, a master and a slave with force sensors became unstable during the slave contacted a stiff environment. Using the one DOF experimental master-slave system, this section shows too small impedance of the virtual model make the system unstable when a load (or an environment) of the slave changes greatly. We can remove this instability with large impedance of virtual model, but this

large impedance prevents the light motion during the slave does not has any load.

The subsection 4.1 propose the way to realize a master-slave system that keeps stable when the load of the slave changes and can move lightly during the slave is free. The advantage of this way is shown in subsection 4.2.

4.1 Parameter Determination

The energy stored and lost by the virtual model, $E_v(t) \in \mathbb{R}$, can be split in three parts as

$$E_v(t) = E_M(t) + E_D(t) + E_K(t) \qquad (35)$$

where $E_M(t)$, $E_D(t)$, $E_K(t) \in \mathbb{R}$ are the energy stored by the inertia, lost by the damping and stored by the stiffness about the position of this model. They are represented with the position and physical parameters of the virtual model defined in (20):

$$
\begin{aligned}
E_M(t) &= \frac{1}{2} M_v \dot{p}_v^2(t) \\
E_D(t) &= \int_0^t D_v \dot{p}_v^2(\tau) d\tau \qquad (36) \\
E_K(t) &= \frac{1}{2} K_v p_v^2(t)
\end{aligned}
$$

The human operator and the remote environment put energy into the master-slave system, exerting the force and moving the master and slave. This input energy $E_i(t)$ can be represented with the external forces, $F_m(t)$ and $F_s(t)$, and the positions, $p_m(t)$ and $p_s(t)$, as

$$E_i(t) = \int_0^t F_m(\tau) \dot{p}_m(\tau) d\tau + \int_0^t F_s(\tau) \dot{p}_s(\tau) d\tau \quad (37)$$

$E_v(t)$ must be equal to $E_i(t)$ ideally for all the time t. But these two energy do not coincide, because the positions of the master and the slave differ slightly from that of the virtual model in the real master-slave system.

When this master-slave system become unstable, it produces some power and works against the human operator and the remote environment. All the motion of the system increases $E_v(t)$ by loss of the damping of the virtual model.

The stable motion of the system increase $E_i(t)$: Some part of power from the human operator is lost by the damping, and the remaining power is transmitted from the slave to the remote environment. The equation (37) deals with the power from the system to the remote environment as the negative energy input. Absolute of this energy is smaller than that of the input from the operator.

In the equation (37), unstable motion of the system decreases $E_i(t)$ because the power flows from the system to the human operator and the remote environment.

The authors propose to use these energy information to stabilize the master-slave system as

$$D^* = \frac{\delta E}{\dot{p}_v^2(\tau) \delta \tau} \qquad (38)$$

$$
D_v = \begin{cases}
D^+ & (D^+ < D^*) \\
D^* & (D^- < D^* < D^+) \qquad (39) \\
D^- & (D^* < D^-)
\end{cases}
$$

where $D^* \in \mathbb{R}$ is the new damping parameter of the virtual model and is determined dynamically from $\delta E = E_i(\tau) - E_v(\tau)$ and the velocity $\dot{p}_v(t)$. $\delta \tau$ is a certain small time period on the time τ. D^+ and D^- are an upper and lower limit of D^*.

D^* acts as damper to reduce δE, because D^* becomes large when the system is unstable ($\delta E \gg 0$). Not only D^* makes $\delta E(> 0)$ close to zero, but also $\delta E(< 0)$ close to zero with its negative damping. This negative side of the damping does not relate to the stabilization directly because $\delta E(< 0)$ does not indicate instability, but this negative side is necessary to keep δE nearly equal to zero and to act it as an indicator of the stability with its sign for all time.

4.2 One DOF Slave and Master Experiments

The experimental master-slave system consists of two motors and a controller of the system: the one is master and the other is slave. The two motors are geared DC motors with the torque sensors, and each has the bar attached orthogonally to its drive shaft in order to actuate the external environments (the human operator and the remote environment). Table I shows the mechanical parameters of the master and slave. The positions of the master and the slave are measured with the optical encoders attached to the motor shaft. The sampling time was 0.96[ms].

In this experiments, the slave bar lifted the wired weight (700[g]) as the load which made the torque 0.39 [Nm] by gravity. When the slave put the weight on the table, the slave can move without loads in the remote environment. The human operator changed the load of the slave as he or she varied the position of the master (and the slave).

The Figures 5 and 6 shows the advantage of the parameter determination proposed in the subsection 4.1. The top plots of this two figures show the positions of the master and slave, and the middle show the
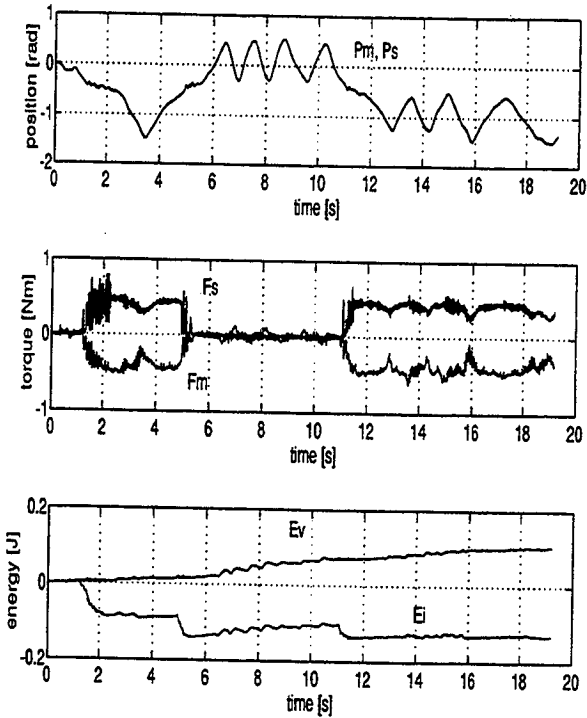
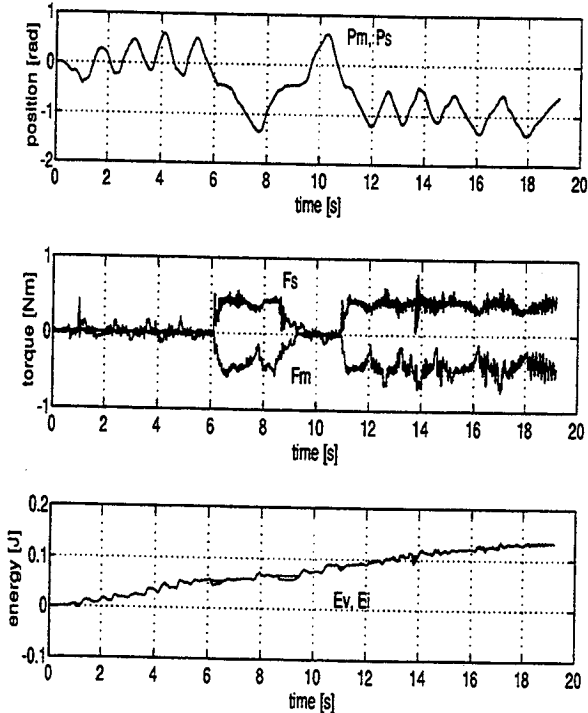Figure 5: Experimental result with fixed damping parameter of virtual model.

Figure 6: Experimental result with variable damping parameter of virtual model.

Table I: Mechanical parameter of master and slave

	Slave System	Master System
Inertia [kgm²]	0.020	0.0090
Damping [Nms]	0.44	0.070

Inertia and damping is measured about output side of gear.

Table II: Parameter of Virtual Mode

	Virtual Model
Inertia [kgm²]	0.005
Damping [Nms]	0.006

torques. The position of the slave coincides with that of the slave, while the torque of the master has the similar form to that of the slave, in each figure.

The considerable difference between the two figures is in the form of the bottom plots. The system showed Figure 5 when it used the fixed damping parameter of the virtual model, as shown in Table II. The inertia and damping of the virtual model were much smaller than that of master and the slave. This small impedance gave the light motion to the system (see the two torques became close to zero during the system moved, the middle plot in the Figure 5). But it also caused oscillation when the load was added on the slave or removed from it. During this oscillation occurred, the input energy to the system, E_i, decreased although the lost and stored energy of the virtual model increased.

The system did not shows this oscillation when it used the dynamically determined damping parameter using the way proposed in subsection 4.1. We set the parameters in (38), (39) as

$$\delta\tau = 0.96\ [ms] : \text{Sampling Time}$$
$$D^+ = 0.3\ [Nms]$$
$$D^- = -0.3\ [Nms]$$

The input energy E_i coincided with the energy of the virtual model, E_v, for almost time. E_i became smaller than E_v when the slave was given the load, but E_i coincided with E_v again by the working of the variable damping parameter.

5 Conclusion

The authors include the virtual model which has the physical dynamics, inertia, damping, and stiffness parameter, in the master-slave system. We proposed that the slave system shares the dimensions of its work space with the human operator to make the remote task easy for the human operator. This master-slave system must have the information about the remote task (*e.g.*,the object model in the remote space, the dimensions which the slave can make up for) and must be able to control positions explicitly. We suggest that the one DOF master can control one dimension of the slave work space with the force feedback.

The mechanical dynamics of the master-slave system can be changed with that of the virtual model, which is determined arbitrary. The small impedance of the virtual model leads to the small impedance of the whole system and realizes the accurate communication about the force and position between the human operator and the remote environment. But too small impedance causes instability on the system, and the minimal impedance with stability changes as the slave load changes.

The authors also propose to determine the damping factor of the virtual model dynamically and show the way to do it. This damping factor becomes large to stabilize the system during the system becomes unstable, comparing the input energy to the system with the stored and lost energy of the virtual model. We showed the advantage of the dynamically determined damping by the experiments with one DOF master-slave system.

Acknowledgements

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