Tele-Bilateral Impedance Control for Master-Slave Systems[†]

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With an increase of needs of tele-operation in several applications, e.g., deep sea or space exploration and tele-surgery, many researchers studied bilateral master-slave tele-operator systems especially after a novel and simple method using a scattering transformation to overcome the instability due to transmission delays was proposed. In this paper we propose a bilateral master-slave manipulator system in which the slave impedance can be adjusted by an operator in a bilateral fashion. The stability of the system for the time delay is also discussed, and the effectiveness of the system is shown by experiments.

Key Words: bilateral control, master-slave system, impedance control, time delay

1. Introduction

In the recent years many researchers studied bilateral master-slave tele-operator systems especially after Anderson and Spong proposed a novel and simple method to overcome the instability due to transmission delays.¹⁾²⁾³⁾ For the master-slave system without time delay, so called impedance matching control which ensures the robust stability has been widely applied for to improve performance of the system.⁴⁾⁵⁾ Remote human adjustable impedance control method is also studied for such systems.⁶⁾⁷⁾ In such control systems, the performance of the system were analyzed basically based on liner control system theory.

In the paper by K.Ito and T.Tsuji it was pointed out that there is a bilinear impedance control mechanism efficiently implemented in human motor control systems, and the controller of the human arm has suitable non-linear properties, i.e. the movement of the arm is controlled by the difference of the generated forces by flexion and extenrtioun, and the impedance is adjusted by the sum of those forces.⁸⁾ So if we intend to construct human like master-slave systems, it is a good idea to mimic the control strategy. In this paper we propose a bilat-

eral master-slave manipulator system with time delay in which the impedance characteristics of the slave arm can be adjusted by a human operator in a bilateral fashion. The impedance property is realized by a kind of bilinear model as in the human motor control system. We have analyzed the stability of the system based on a passivity theory and the stability is proven rigorously in¹³⁾. The control strategy of the proposed system is briefly discussed and the efficiency of the proposed system is shown by some experiments using a hardware system.

2. Structure of the Whole System

Structure of the system discussed in this paper is shown in Fig. 1, which consists of a conventional bilateral master-slave system and a grip with which an operator can specify a net impedance of the slave system in a bilateral fashion manually, i.e. the operator can feel the compliant quantity in the slave system over controlling the slave impedance characteristics. The meanings of the symbols in Fig. 1 are given in Table 1 and their concrete meanings are defined later. In the following discussion the control algorithm is considered in a joint coordinate frame, however, similar discussion can be carried out in a task coordinate system with simple modifications. Furthermore, master-slave system is assumed to be bilateral but the algorithm can be used for unilateral systems.

2.1 Function of the grip

The configuration of the grip with which the operator can specify the impedance is shown in Fig. 2, and it is assumed that the grip is mounted on the master arm. Since the actuated torque at the joint of the grip is determined

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Table 1 Symbols in Fig. 1

τ_m	command force to the master from the operator
τ_e	reaction force to the slave from the environment
q_{rm}	augmented movement of the master
q_{rs}	augmented movement of the slave
τ_o	impedance control signal
τ_i	net compliant quantity of the slave
θ	compliant measure displayed to the operator

Fig. 1 Block diagram of the system.

according to the amount of tracking error between the master position and slave one in the system, the operator can see the compliant quantity as the resultant angle of the grip. On the other hand, the impedance in the slave system is proportional to the gripping force measured by a force sensor attached to the grip, i.e., the impedance becomes big if the operator grasps the grip rigidly, vice versa. In the system we assume that the grip is equipped with the master system so that the gripping operation does not affect the operation of the master system, e.g., the movement of master arm is controlled by a human arm and the gripping operation is done by a hand.

In this system the dynamics of the grip is assumed to be given by the following simple equation:

Fig. 2 Configuration of the grip.

$$J\ddot{\theta} + \mu\dot{\theta} + k\theta = \tau_i - \tau_o, \quad (1)$$

where J, μ, k are an inertia, damping coefficient and spring constant, respectively. τ_i is a torque signal representing the compliant quantity determined in the next section and τ_o is a torque exerted by the operator against the move-

ment of the grip. We also assume that τ_o can be represented by a linear impedance:

$$\tau_o = G_o(k_{dh}\dot{\theta} + k_{ph}\theta) \quad (2)$$

where k_{dh} and k_{ph} are viscosity and spring constant of the hand, and G_o is a gain. (Though the above equation does not include the inertia term for simplicity, the following discussion can be carried out similarly where the inertia term exists. There might be an offset force exerted by the operator, however, it can be treated separately from the impedance force if k_{dh} and k_{ph} and the states of the grip are known exactly. Therefore, the term is neglected in the following discussion. Moreover, though we assume that k_{dh}, k_{ph} are constant, they are not constant in general. They, however, can be assumed to be constant in a short time if the operator does not change the values with intensions. (Study of the general cases should be a future work.

In the proof of the stability of the whole system later, we will use passivity formulation, then we consider passivity of the grip system. The input-output characteristic of the block is described by the relationship between τ_i and τ_o where τ_i is input and τ_o is output, and the transfer function is given by

$$H(s) = \frac{\tau_o(s)}{\tau_i(s)} = \frac{G_o(k_{dh}s + k_{ph})}{Js^2 + (\mu + G_o k_{dh})s + k + G_o k_{ph}}. \quad (3)$$

Simple calculation shows that the passivity is satisfied if

$$k_{dh}(\mu + G_o k_{dh}) \geq Jk_{ph}, \quad (4)$$

and all coefficients are positive. Note that the above condition is easily satisfied if the design parameter μ and J is properly selected.

2.2 Bilateral master-slave system

We assume that dynamic equations of the master and slave arms are given by

$$\tau_{cm} + \tau_m = D(q_m)\ddot{q}_m + C_m(q_m, \dot{q}_m)\dot{q}_m + G_m(q_m) \quad (5)$$

$$\tau_{cs} - \tau_e = D(q_s)\ddot{q}_s + C_s(q_s, \dot{q}_s)\dot{q}_s + G_s(q_s), \quad (6)$$

where s and m stand for "slave" and "master", respectively, and D, C, G are inertia, Coriolis and centrifugal and gravity term, respectively. $q_m, q_s \in R^n$ are general coordinate vector of the systems, and τ_m is a force exerted by the operator and τ_e is a reaction force from the environment, which appear in the conventional bilateral master-slave system, and τ_{cm}, τ_{cs} are control input for the systems. In the following, viscosities at the joints are as-

sumed to be zero for simplicity, however, the terms can be easily compensated for by a local feedback.

First we determine a control input for the master arm. In the paper we use a so-called computed torque method which makes the system linear for the difference between the operator torque and the slave torque exerted by the environment since the local system can be easily identified and the parameters of the system can be obtained accurately. The actual control input τ_{cm} is determined by

$$\tau_{cm} = C_m(q_m, \dot{q}_m)\dot{q}_m + G_m(q_m) - \tau_m + D_m(q_m) \left(\frac{1}{\epsilon} (\tau_m - \tau_e) - \Lambda \dot{q}_m - \mu_m q_{rm} \right) \quad (7)$$

where

$$q_{rm} = \dot{q}_m + \Lambda q_m \quad (8)$$

and ϵ is a small positive constant, and Λ and μ_m are constant positive definite matrices. Using the control, the closed loop system becomes

$$\tau_m - \tau_e = \epsilon(\dot{q}_{rm} + \mu_m q_{rm}). \quad (9)$$

Please notice here that since the manipulation property for the operator depends on the set of parameters $(\epsilon, \mu_m, \Lambda)$, they should be carefully selected for tasks in addition to an impedance center. Next we consider the control input for the slave system. Though we can use a similar control method to the master system, we employ a model based control given by

$$\begin{aligned} \tau_{cs} &= D_s(q_s)\ddot{q}_{rs} + C(q_s, \dot{q}_s)\dot{q}_{rs} \\ &+ G_s(q_s) + K_{pd}\tilde{e} + \tau_{co} \end{aligned} \quad (10)$$

where q_{rs} and $\tilde{e}$ are defined as

$$\tilde{q}_{rs} = q_{rm} - \Lambda q_s \quad (11)$$

$$q_{rs} = \dot{q}_s + \Lambda q_s \quad (12)$$

$$\tilde{e} = q_{rm} - q_{rs} \quad (13)$$

and K_{pd} is a positive definite matrix and τ_{co} is an adjustable term by the operator defined later. The reason why we use the above control is that the control algorithm can be easily modified into adaptive controllers.⁹⁾¹⁰⁾ Using the control law, we have the following closed loop system:

$$D_s(q_s)\ddot{\tilde{e}} + C(q_s, \dot{q}_s)\dot{\tilde{e}} + K_{pd}\tilde{e} + \tau_{co} = \tau_e. \quad (14)$$

Please note that we can consider $[\tilde{e}^T, \dot{\tilde{e}}^T]^T$ as a state of the above system, and the actual error between q_m and q_s is just a filtered output of $\tilde{e}$. According to the closed loop system, we employ the adjustable term, τ_{co} , as

$$\tau_{co} = \tau_o \tilde{e} \quad (15)$$

so that the impedance of the slave system can be adjusted by the force given by the operator and the stability of the whole system can be maintained. Though the details are discussed in the next section, please note here that the impedance characteristics of each freedom can be independently specified in a certain degree by a selection of Λ as seen in eq. (15).

3. Stability of the Whole System

Since the stability of the system is shown by the passivity of each subsystem in Fig. 1, we consider the passivity of the master and the slave system because the passivity of the grip system is assured already as in the last section.

3.1 Passivity of the master system

First we consider the passivity of the master system. The passivity condition of the system is given by

$$\int_0^t \begin{bmatrix} q_{rm}^T & -q_{rm}^T \end{bmatrix} \begin{bmatrix} \tau_m \\ \tau_e \end{bmatrix} dt \geq 0 \quad \text{for } \forall t > 0, \quad (16)$$

considering about the direction of the signal flows. In order to show the passivity we consider a Lyapunov like function, V_m , given by

$$V_m(t) = \frac{1}{2} q_{rm}^T q_{rm} \geq 0. \quad (17)$$

Differentiating the above equation using eq. (9), we have

$$\begin{aligned} \dot{V}_m &= q_{rm}^T ((\tau_m - \tau_e)/\epsilon - \mu_m q_{rm}) \\ &= q_{rm}^T (\tau_m - \tau_e)/\epsilon - q_{rm}^T \mu_m q_{rm}. \end{aligned} \quad (18)$$

Therefore we have

$$q_{rm}^T (\tau_m - \tau_e) = \epsilon (\dot{V}_m + q_{rm}^T \mu_m q_{rm}), \quad (19)$$

and integrating the above equation from 0 to t we have

$$\begin{aligned} \int_0^t \begin{bmatrix} q_{rm}^T & -q_{rm}^T \end{bmatrix} \begin{bmatrix} \tau_m \\ \tau_e \end{bmatrix} dt \\ = V(t) - V(0) + \int_0^t q_{rm}^T \mu_m q_{rm} d\tau. \end{aligned} \quad (20)$$

If we assume that $V_m(0)$ is zero, the desired result is obtained. Note here that the passivity relationship is considered to q_{rm} not but to $\dot{q}_m$. This property is discussed later.

3.2 Passivity of the slave system

Similarly to the master system, the condition of the slave system is given by

$$\int_0^t \begin{bmatrix} -\tau_i & q_{rm}^T & -q_{rs}^T \end{bmatrix} \begin{bmatrix} \tau_o \\ \tau_e \\ \tau_e \end{bmatrix} d\tau \geq 0, \quad \text{for } \forall t > 0 \quad (21)$$

since it has 3 ports. We consider a Lyapunov function candidate defined by

$$V_s(t) = \frac{1}{2} \tilde{e}^T D_s(q_s) \tilde{e} \geq 0. \quad (22)$$

Differentiating the above equation using eq. (14), we have

$$\begin{aligned} \dot{V}_s &= \tilde{e}^T (\tau_e - C(q_s, \dot{q}_s) \tilde{e} - K_{ds} \tilde{e} - \tau_{co}) \\ &\quad + \frac{1}{2} \tilde{e}^T \dot{D}_s(q_s) \tilde{e} \\ &= \tilde{e}^T \tau_e - \tilde{e}^T K_{pd} \tilde{e} - \tau_o \|\tilde{e}\|^2 \\ &\quad + \frac{1}{2} \tilde{e}^T (\dot{D}_s(q_s) - 2C_s(q_s, \dot{q}_s)) \tilde{e}. \end{aligned} \quad (23)$$

If we define the signal τ_i as

$$\tau_i := \|\tilde{e}\|^2 \quad (24)$$

and using the skew symmetry of $\dot{D}_s(q_s) - 2C_s(q_s, \dot{q}_s)$, we have

$$\begin{aligned} \dot{V}_s + \tilde{e}^T K_{pd} \tilde{e} &= -\tau_i \tau_o + \tilde{e}^T \tau_e \\ &= -\tau_i \tau_o + (q_{rm} - q_{rs}) \tau_e. \end{aligned} \quad (25)$$

Since the right hand-side of the above equation is the integrand of the passivity condition, we obtained the desired result if we assume $V_s(0) = 0$. In the above discussion the stability of the whole system can be proven by the passivity principle, e.g. ¹¹⁾. Furthermore, if the external input τ_e is zero, the tracking convergence of the slave system to the master can be assured as follows, i.e., $e(t) \rightarrow 0$ ($t \rightarrow \infty$) where

$$e := q_m - q_s. \quad (26)$$

If τ_e is zero, it can be considered that the slave and the grip system is controlled unilateral by the master system since there is no feedback from the slave system. Then it is sufficient to consider about a system which consists of only the slave system and the grip. Let consider the following Lyapunov like function:

$$V(t) = \frac{1}{2} \tilde{e}^T D_s(q_s) \tilde{e} + \int_0^t \tau_i \tau_o d\tau \geq 0. \quad (27)$$

The semi-positivity is ensured because of the passivity of the grip system. Taking a derivative of V by time along the system dynamics, we have

$$\begin{aligned} \dot{V} &= \tilde{e}^T D_s(q_s) \dot{\tilde{e}} + \frac{1}{2} \tilde{e}^T \dot{D}_s \tilde{e} + \tau_i \tau_o \\ &= \tilde{e}^T (-K_{pd} \tilde{e} - \tau_o \tilde{e}) + \frac{1}{2} \tilde{e}^T (\dot{D}_s - 2C_s) \tilde{e} + \tau_o \tau_i \\ &= -\tilde{e}^T K_{pd} \tilde{e} \leq 0. \end{aligned} \quad (28)$$

Integrating the both side of the above equation, we have

$$\begin{aligned} V(t) - V(0) &= \int_0^t -\tilde{e}^T K_{pd} \tilde{e} d\tau \\ &\leq - \int_0^t \lambda_{min}(K_{pd}) \|\tilde{e}\|^2 d\tau. \end{aligned} \quad (29)$$

Therefore, we have

$$\int_0^t \|\tilde{e}\|^2 d\tau \leq \frac{V(0) - V(t)}{\lambda_{min}(K_{pd})}. \quad (30)$$

From the monotonically decreasing of $V(t)$ and the positiveness of K_{pd} , $\tilde{e}$ is in L_2 . Since

$$\dot{e}(t) = -\Lambda e(t) + \tilde{e}(t), \quad (31)$$

standard arguments deduce that $e \in L_2 \cap L_\infty$ and $e(t) \rightarrow 0$ ($t \rightarrow \infty$). ¹²⁾

4. Compensation of Time Delay

In this section we consider about time delay in transmission networks. Since the design of the control system is based on the passivity formulation, if the transmission network is passive, the stability of the whole system can be assured. Such a method has been proposed by ¹⁾ and we employ the method in the system. Following the method, signals transmitted between the grip system and the slave system and ones between the master and slave systems are determined as follows, where the time delay is assumed to be T .

• Signals between grip and slave system

The signals communicated between the grip system and the slave system are as follows:

$$\tau_{os}(t) = \tau_o(t - T) - \tau_{im}(t - T) + \tau_i(t) \quad (32)$$

$$\tau_{im}(t) = \tau_i(t - T) - \tau_o(t) + \tau_{os}(t - T) \quad (33)$$

where

τ_{os} : signal used as τ_o in the slave system

τ_{im} : signal used as τ_i in the master system

• Signals between master and slave systems

The signals transmitted between the master and the slave systems are defined as follows:

$$\tau_{em}(t) = \tau_e(t - T) - q_{rms}(t - T) + q_{rm}(t) \quad (34)$$

$$q_{rms}(t) = q_{rm}(t - T) - \tau_e(t) + \tau_{em}(t - T) \quad (35)$$

where

τ_{em} : signal used as τ_e in the master system

q_{rms} : signal used as q_{rm} in the slave system

If we use the method above, sometimes there exists undesirable oscillations in the network and we employ scattering filter in the network. ³⁾ An equivalent electric circuit is shown in **Fig. 3**. In the figure, an offset torque, f_h , which is an intentional torque estimated by the model of the human hand, is also included for the completeness though the signal was not discussed in the above. The signal is, however, can be simply sent to the slave system without scattering and the value is added to $\tau_o \tilde{e}$ since the value is assumed to be positive or the signal can be clipped into a positive value. Of course, we note that if we want to estimate f_h , a precise model and the parameter of the human hand must be known.

Usually, the passivities between the velocities and the force of the operator and the environment are assumed, however, we must consider the passivities about q_{rm} and q_{rs} . This assumption may restrict the selection of Λ which is a trade-off between the stability and the tracking performance if the conventional passivity assumption is only satisfied, i.e., $sI + \Lambda$ and $(sI + \Lambda)^{-1}$ are inserted, and the effects should be considered in Fig. 3.

Fig. 3 Equivalent electric circuit of the system.

5. Experiments

In this section we will show some experimental results in order to show the properties of the proposed method. Concerning about simulations with various parameters and time delays, please refer to ¹³⁾.

5.1 Experimental system

We have constructed an experimental system shown in Fig. 4. In the system the master and the slave arm have a translational single degree of freedom, and each arm is actuated by a D.C. motor and a transmission screw. At the tip of each arm a load sensor is attached to measure τ_m and τ_e , and the grip system is realized as in Fig. 2 and is mounted on the master arm.

5.2 Parameters of the system and the controller

The parameters of the master, slave and grip system were identified as in Table 2. Using the viscosity parameter each arm is compensated locally so that it can be assumed that there is no viscosity in the system. As in the table, we used a grip system with a sufficient large damping coefficient which is determined based on an estimate of k_{ph} and the values in a reference ¹⁴⁾ in order to satisfy the passivity condition of eq. (4) where the estimated value of k_{ph} was in a range between 6 and 20 [Kgm/rad].

Fig. 4 Experimental master-slave system with a grip.

Table 2 Parameters of the systems

Parameter	Mass(Inertia)	Viscosity
Master arm	120 [Kg]	1090 [Ns/m]
Slave arm	76 [Kg]	970 [Ns/m]
Grip	2.5×10^{-4} [Kgm ²]	13.5 [Nms]

Table 3 Parameters of the controller.

G_o	1.0	K_{pd}	190
ϵ	0.10	G_{τ_e}	0.1
μ_m	0.01	G_{τ_i}	10
Λ	9.1	k	0

The control parameters in the previous section are set as in Table 3.

In the actual implementation of the controller two gains were introduced, namely G_{τ_e} and G_{τ_i} as in Table 3, in order to make the effect of the impedance adjustment signal τ_{co} sufficiently large with normal gripping operations, and the gains are multiplied to τ_e in eq. (7) and to τ_{co} in eq. (10), respectively. If $G_{\tau_e} G_{\tau_i} = 1$ is satisfied, inequalities of (16) and (21) are maintained with changing τ_e to $G_{\tau_e} \tau_e$, the gains does not affect the stability of the system. The parameters, however, might cause instability problem in general and it could be compensated as in ¹⁾. If we modify the mechanical structure of the grip, the modification may be excluded. The control period was 1.45 [msec] in the all experiments.

5.3 Experimental results

First, we will show the effect of τ_o to the movement of the slave arm. In order to show the effect clearly, G_{τ_e} was set to zero in this case, i.e., τ_e did affect the movement of the grip but not that of the master arm. In the experiment the external force τ_e was exerted as a step input at about 10 [N] by a spring. During the constant disturbance was given to the slave system, the grip was free at the beginning and it was grasped rigidly after 11

[sec]. As shown in **Fig. 5** and **Fig. 6**, when the grip is not grasped and τ_o is zero, the movement of the slave system deviated from that of the master system. The slave movement, however, did almost coincide with that of the master system after the grip was grasped rigidly. It is also observed that the gripping force τ_o was well damped after a second. In **Fig. 7** responses of $\|\tilde{e}\|$ and θ during the experiment are shown where dotted line shows the angle of the grip. From the figure, saturations of the rotation due to a hardware limitation can be seen. In the proposed algorithm, as τ_{co} depends on the square of $\|\tilde{e}\|$, θ can be easily trapped to the hardware limitation. The property, however, can be overcome by the following modification 15).

$$\tau_i = \|\tilde{e}\|$$

$$\tau_{co} = \begin{cases} \tau_o \tilde{e} / \|\tilde{e}\| & (\|\tilde{e}\| \neq 0) \\ 0 & (\|\tilde{e}\| = 0) \end{cases}$$

and introduction of k . The selection of the control may depend on tasks.

Fig. 5 Responses of q_m and q_s in the first experiment.

Second experiment shows the stability of the whole system when the external force τ_e is reflected to the master arm, i.e., $G_{\tau_e} = 0.1$, and the time delay was set 100 [msec]. The external force τ_e was generated by attaching a spring to the tip of the slave system where the spring constant was 98 [N/m].

Solid and dotted lines show q_s and q_m , respectively, in **Fig. 8** and **Fig. 9**. **Fig. 8** shows the results when we did not use the scattering technique. In the experiment the spring was pulled at about 10[N] in a short time once and it is fixed at a fixed position. From the figure we can observe oscillations in the system and see that the system is not stable. On the other hand, **Fig. 9** shows the result when the scattering transformation was used. In this ex-

Fig. 6 Response of τ_o in the first experiment.

Fig. 7 Response of $\|\tilde{e}\|$ and θ in the first experiment.

periment the spring was pulled and held about every two seconds. From the figure it can be seen that the oscillation was well damped and the system was stable. Comparison of the two figures convinces us the effectiveness of the scattering technique to our system.

In order to check the function of the system, we implemented the proposed algorithm to a system which consists of the master system used in the above experiment and a PUMA arm, and a peg in hole operation was executed where we used PUMA manipulator as a 3 degree of freedom planar manipulator in a vertical plain. Please see a report ¹⁶⁾ for the details of the experiment.

6. Concluding Remarks

We have proposed a bilateral master-slave system in which an impedance characteristics of the slave manipulator can be controlled in a bilateral fashion by an operator. The stability of the proposed system has been analyzed based on passivity formulation under an assumption especially about the operator. Furthermore, compensation

Fig. 8 q_m and q_s in the second experiment without the scattering technique.

Fig. 9 q_m and q_s in the second experiment with the scattering technique

of the time delay due to the transmission lines were also considered. Some experiments have convinced the effectiveness of the proposed control system.

In this paper we assumed that the characteristics of the operator can be modeled as a simple linear impedance, however, the characteristics is not so simple and further studies should clarify the problem. Furthermore, the intentional force f_h is assumed to be a time dependent function, however, it may be a function of the state. So it should be also checked how the feedback nature of f_h affects the stability of the whole system. Since the manipulation efficiency of the whole system should depend on time delay and the design of controller for the slave system in addition to the selection of ϵ, μ, Λ since the reaction forces depend on the condition of the interactions between the slave system and the environment, these factors should be also examined before practical applications.

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