ISSN 0005–1144
ATKAAF 46(1–2), 5–16 (2005)

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Bilateral Motion Control for Abstraction and Reproduction of Real World Force Sensation

UDK 004.6:654.9
IFAC 5.9.3;2.5

Original scientific paper

In recent years, skill preservation of an expert and skill education for young technical workers have been serious issues in medical and production fields. The best way which young technical workers learn the ripe skill is that an expert teaches them. However, unfortunately, experts have lessened in these years. So, if digital skill preservation like a haptic database is attained, it may become an innovative solution of the above problem. Thus, as the fundamental technology for development of the haptic database, this paper proposes abstraction and reproduction methods on bilateral control of real world force sensation, and reconstruction of real world environment as well. In the abstraction mode, a master-slave system is composed, and the action-reaction law is attained through bilateral control. Later, based on acceleration information, the force, position and velocity of both master and slave systems are estimated and obtained. In the reconstruction mode, an environmental model is reconstructed based on the obtained data from real-world. Next, by using reproduction mode on master side, the operator would feel the force sensation from the obtained environmental model. Here, the proposed system is able to store the bilateral real-world force sensation to a sensation database. Finally, the experimental results show the validity of the proposed method.

Key words: bilateral motion control, haptic interface, haptic database, real world force sensation

1 INTRODUCTION

In these years, skill preservation of an expert and skill education for young technical workers have been serious issues in medical and production fields. These problems have dominantly occurred in the medical or production fields because of the lack of the experts. The best way which young engineers learn the ripe skill is that an expert teaches them. However, there are not enough experts to teach all of them. So, if digital skill preservation like a haptic database is attained, it may become an innovative solution of the above problem. However, haptic information is bilateral information of action and reaction. Therefore, a haptic database should be bilateral. As a configuration type of the system in order that the system becomes bilateral, composing the system of master system and slave system is conceivable.

Bilateral control is one of the technologies for teleoperation that the system is composed of master system and slave system. Recently, there are many researches on it. Many architectures of bilateral control have been proposed. Hannaford proposed the ideal conditions of forces and positions between master system and slave system based on hybrid matrix [1]. Later, the ideal conditions which were proposed by Hannaford were advanced, and they were discussed as the stability and transparency by D. A. Lawrence [2]. Then, Hashtrudi-Zaad et al. proposed the architecture which was designed to earn the transparency between master system and slave system [3, 4]. Yokokohji et al. also proposed the bilateral architecture which was designed to earn the transparency [5]. Meanwhile, the stability analysis for the bilateral control with time delay has been done [6]. Kosuge et al. proposed the bilateral control architecture with the task-oriented virtual tool which is based on the idea of impedance control [7, 8]. In addition, the experimental comparison of some bilateral architectures was done [9]. However, since the emphasis of the conventional bilateral control architectures is on earning of stability and transparency, they was not able to transmit vivid enough force sensation. Thus, the control method to which compliance control was applied for transmission of vivid force sensation, being based on control stiffness and mechanism of contact with environment, was proposed [10]. Although many researches on bilateral control have been done as described above, few researches on reproduction of haptic information from the environment have been done. Moreover, in many conventional researches on haptics, the environment is almost

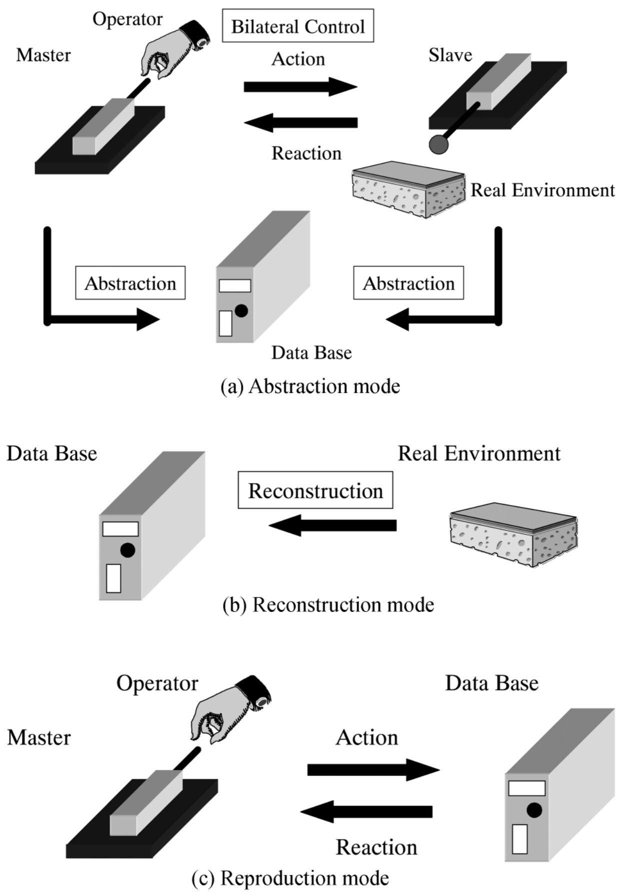


Fig. 1 Pictorial description of force sensation recorder (FSR)

not real but virtual [11–14]. Since the system is not able to transmit the vivid force sensation from the real environment in the conventional bilateral control, the conventional bilateral control is not able to be applied to haptic database. So, this paper proposes the new bilateral architecture which is able to transmit the vivid force sensation. Additionally, this paper also proposes the new conception and new system of force sensation recorder (FSR) which is able to abstract force sensation from the real environment and is able to reproduce it, as a fundamental technology for evolution of haptic database. Figure 1 shows the interchange of force sensation in FSR. The proposed acquisition system in this paper has three modes; that is to say these are the abstraction mode, the reconstruction mode, and the reproduction mode. First, in the abstraction mode, a master-slave system is composed and the law of action and reaction is attained by bilateral control. The system abstracts not only position and force information based on acceleration information but also environmental information like environmental impedance from the real environment (Figure 1 (a)). Secondly, in the reconstruction mode, an environment model is reconstructed from the obtained data of the real environment (Figure 1 (b)). Finally, in the reproduction mode, only the master system is prepared. Human operates the master system and feels force sensation from the environmental model which is reconstructed in the reconstruction mode (Figure 1 (c)). As a result, the proposed system is able to store the real environment as a bilateral database.

This paper is organized as follows. The abstraction mode which is based on bilateral control is considered in section 2. In section 3, modeling method of the real environment based on stiffness and viscosity is shown as the reconstruction mode. In section 4, the reproduction mode is described. Experimental results are presented in section 5. Finally, as the conclusions, this paper is summarized.

Table 1 **Parameters**

M	Mass
F	Force
x	Position
t	Time
dt	Dimensionless time
C_p	Position regulator
C_f	Force servoing
K_t	Force coefficient
k	Spring coefficient
D and d	Viscosity coefficient
Z	Impedance
I_a	Current value
g	Observer gain
s	Laplace operator
(superscript)*cmd*	Command value
(superscript)*ref*	Reference value
(superscript)^	Estimated value
(superscript)*res*	Response value
(subscript)*m*	Master system
(subscript)*s*	Slave system
(subscript)*e*	Environment
(subscript)*C*	Coulomb friction
(subscript)*n*	Nominal value
(subscript)*com*	Common mode
(subscript)*dif*	Differencial mode
(subscript)*dis*	Disturbance observer (DOB)
(subscript)*reac*	Reaction force estimation (RFE) by DOB
(subscript)*k*	Spring
(subscript)*d*	Damper

The parameters which are used in this paper are shown in Table 1.

2 ABSTRACTION MODE

In the abstraction mode, the system abstracts the action and reaction information by bilateral control for the realization of the haptic bilateral database. Bilateral control is one of the technologies for teleoperation of master-slave system. The most important in bilateral control is the artificial realization of law of action and reaction between the action force which is applied to master system by the operator and the reaction force which is applied to slave system from the real environment. Then, in order that the law of action and reaction is realized artificially and the system is able to transmit the vivid force sensation, force control and position control must be realized concurrently. However, since the dimension of force information is different from the dimension of position information, the sum of them and the differential in them are not able to be calculated simply. Thus, in this paper, the aim of force control and the aim of position control are standardized in common dimension of acceleration. Then, the novel bilateral control based on acceleration control which is able to realize the aims of force control and position control in the acceleration dimension concurrently is proposed. Moreover, since a disturbance observer is implemented in bilateral control system, the transmission of information based on acceleration control leads to the secureness of robustness [15–17]. So, the proposed bilateral control is designed to transmit information based on only acceleration dimension between master system and slave system in this paper.

A. Disturbance Observer (DOB)

In the conventional motion control, especially in the conventional force control, force sensors have been implemented in so many researches to detect the external force. Most of force sensors detect the strain of the strain gauge. The strain is assumed the external force. However, in this case, it is so difficult to detect only reaction force from the environment which is distorted at the time with contact. Additionally, force sensors have very narrow bandwidth. Thus, force sensation which is detected by force sensors is so dull. Moreover, force sensors detect the external force only at the position where they are implemented. So, force sensors are unfit for transmission of vivid force sensation.

On the other hand, disturbance observer is able to obtain much wider bandwidth than force sensors, due to being able to make the sampling time brief and to being able to increase the observer gain as much as possible. So, disturbance observer is more suitable for transmission of vivid force sensation in motion control than force sensors [18].

A disturbance observer observes disturbance force in the system without using sensors [15, 16]. The block diagram of disturbance observer is shown in Figure 2.

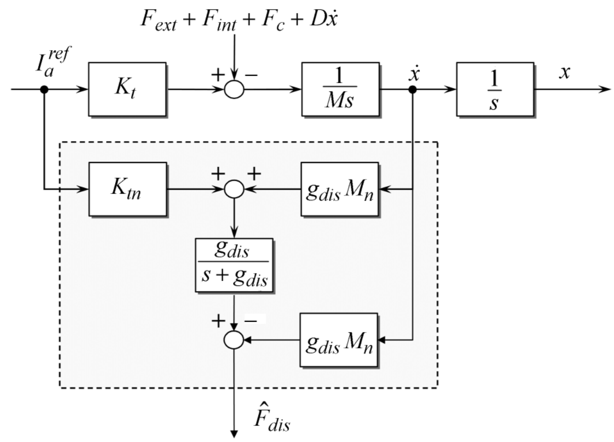


Fig. 2 Disturbance observer (DOB)

In the disturbance observer, the disturbance force is represented as (1)

$$F_{dis}=F_{ext}+F_{int}+F_C+D\dot{x}+(M-M_n)\ddot{x}+ \\ +I_a^{ref}(K_{tn}-K_t) \tag{1}$$

where, F_{ext} means disturbance force which is applied from the external, F_{int} means internal interference disturbance, F_C means coulomb friction, $D\dot{x}$ means viscosity friction respectively. And, $(M-M_n)\ddot{x}$ shows the disturbance caused by mass variation, $I_a^{ref}(K_{tn}-K_t)$ shows the disturbance caused by torque ripple. Then, the disturbance force is estimated by the disturbance observer through the low-pass filter as (2)

$$\hat{F}_{dis}=\frac{g_{dis}}{s+g_{dis}}F_{dis.} \tag{2}$$

The feedback on estimated disturbance force attains the robustness. So, the disturbance observer is able to earn the robustness.

In the actual application, the disturbance observer is effective not only for the disturbance compensation but also for the reaction force estimation (RFE). That is, the disturbance observer is able to estimate the reaction force without using a force sensor by identifying the internal disturbance in the system previously. The transmission of force sensation by bilateral control is based on the action and reaction relationship. The disturbance observer calculates and estimates the reaction force as quickly as possible by increasing the cut-off frequency [15, 16]. The block diagram of the function of reaction force estimation by the disturbance observer is shown in Figure 3.

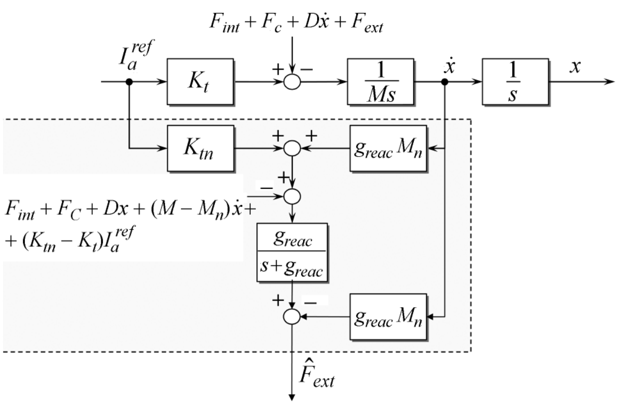


Fig. 3 Reaction force estimation (RFE) by DOB

The disturbance observer estimates only the external force $\hat{F}_{ext}$ as (3)

$$\hat{F}_{ext} = \frac{g_{reac}}{s+g_{reac}}(I_a^{ref}K_{tn} + M_n g_{reac}\dot{x} - (F_{int} + F_C + D\dot{x} + +(M-M_n)\ddot{x} + I_a^{ref}(K_{tn}-K_t))) - M_n g_{reac}\dot{x} = \frac{g_{reac}}{s+g_{reac}}F_{ext}. \quad (3)$$

It is difficult to observe the real mass M and the real force coefficient K_t because they are fluctuant. But, since the bands of fluctuation of them are so narrow, the disturbance forces caused by the variation of them are too small and ignorable. The disturbance caused by coulomb friction F_C and the disturbance caused by viscosity friction $D\dot{x}$ are able to be identified through the constant velocity test.

The architecture of the estimation function by disturbance observer is almost the same as the one of the compensation function by disturbance observer. The disturbance observer also works as an acceleration sensor, since the estimated force $\hat{F}_{ext}$ divided by nominal mass M_n will be in the acceleration dimension virtually as (4).

$$\ddot{x}_{ext} = \frac{1}{M_n}\hat{F}_{ext}. \quad (4)$$

B. Abstraction Method

Abstraction method is based on bilateral control. As the aim for the artificial realization of law of action and reaction between the action force which is applied to master system by the operator and the reaction force which is applied to slave system from the real environment, the relationship of force between master system and slave system is represented as (5)

$$F_m + F_s = 0. \quad (5)$$

The aim of position for tracking of master system and slave system each other is also represented as (6)

$$x_m - x_s = 0. \quad (5)$$

In bilateral control, the coinstantaneous achievements of aims of force and position are required. However, since the dimension of force information is different from the dimension of position information, the sum of them and the differential in them are not able to be calculated simply. Thus, in this paper, the aim of force control and the aim of position control are standardized in common dimension of acceleration. Then, the novel bilateral control based on acceleration control which is able to realize the aims of force control and position control in the acceleration dimension concurrently is proposed. Additionally, in bilateral control, the transmission of the force sensation between master system and slave system in rigid real-time with attaining of the law of action and reaction, the attainment of the robustness in the whole system, and the expandability to the system which has multi degrees of freedom are requisite. In order to fulfill the above requirements, it is proper to design the bilateral control architecture based on acceleration control with disturbance observer. So, the aim of force and the aim of position are transformed into the dimension of acceleration as (7) and (8)

$$\ddot{x}_m + \ddot{x}_s = \ddot{x}_{com}^{cmd} = 0. \quad (7)$$

$$\ddot{x}_m - \ddot{x}_s = \ddot{x}_{dif}^{cmd} \to 0. \quad (8)$$

(7) shows the force servoing based on the acceleration dimension. Thus, in this paper, the force servoing is implemented as (9) to attain the aim of force in acceleration dimension

$$\ddot{x}_{com}^{ref} = C_f(\ddot{x}_{com}^{cmd} - \ddot{x}_{cmd}^{res}). \quad (9)$$

And, the force servoing represented as (9) is shown in Figure 4. This aim of force in acceleration dimension is called »common mode« between master system and slave system in the virtual mode space. On the other hand, (8) shows the position regulator based on the acceleration dimension. To attain the aim of position in acceleration dimension, the position regulator represented as (10) is implemented in this paper

$$\ddot{x}_{dif}^{ref} = C_p \ddot{x}_{dif}^{res}. \quad (10)$$

This position regulator is shown in Figure 5. This aim of position in acceleration dimension is called

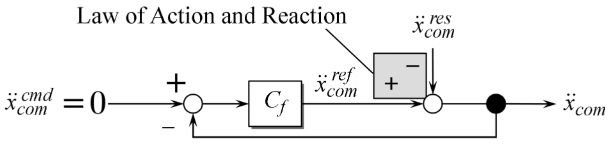


Fig. 4 Force servoing

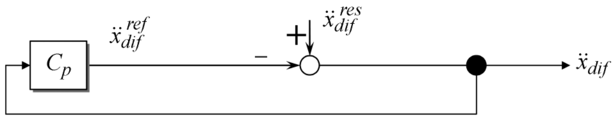


Fig. 5 Position regulator

»differential mode« between master system and slave system in the virtual mode space. Thus, it is able to design the aim force and the aim of position in the acceleration dimension independently, by realizing them based on the common mode and the differential mode which are decoupling together in the mode space [19]. Here, C_f and C_p mean the gain of force servoing and the gain of position regulator respectively. The gains of force servoing and position regulator are represented as (11) and (12)

$$C_f = K_f \tag{11}$$

$$C_p = \frac{1}{s^2}K_p + \frac{1}{s}K_v + K_a. \tag{12}$$

K_f, K_p, K_v and K_a mean the force gain, position gain, velocity gain and acceleration gain respectively. In the general acceleration control, the response varies with the initial conditions. In the case that there is no initial deviation of position and velocity, master system and slave system track each other very well in bilateral control. In the proposed bilateral control, the disturbance observer is implemented. If the ideal condition of disturbance observer is attained, disturbance observer has integration element. So, even if there is a initial deviation of position and velocity, the response is able to converge on the command. In the actual case, it is so difficult to set the cut-off frequency of disturbance observer to be infinity. So, there is a little bit of deviation between the response and the command. However, the deviation is too small. So, the deviation is ignorable. Thus, the proposed bilateral control is also able to attain the precise position tracking between master system and slave system.

As space transformation matrices, the second order Hadamard matrix $\boldsymbol{H}_2$ and inverse of the second order Hadamard matrix $\boldsymbol{H}_2^{-1}$ are used. Since it is easy to calculate the inverse matrix of the second order Hadamard matrix, it is also easy to achieve the transformation between the mode space and the joint coordinate space of master and slave system. These matrices are represented by (13) and (14)

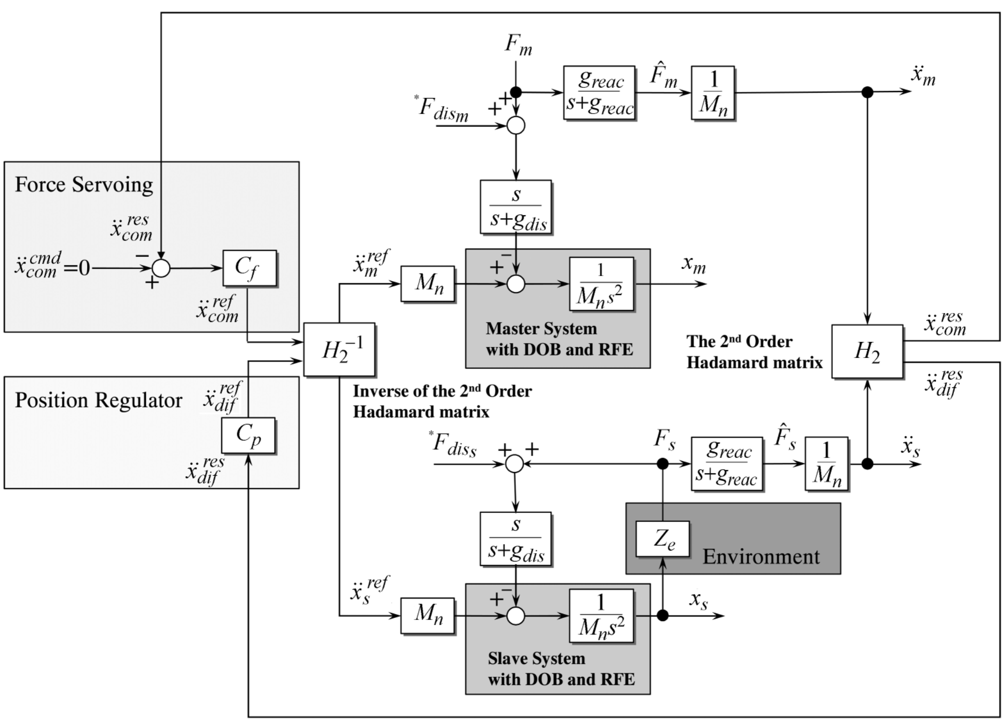


Fig. 6 Abstraction mode

$$\boldsymbol{H}_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \tag{13}$$

$$\boldsymbol{H}_2^{-1} = \frac{1}{2}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}. \tag{14}$$

Then, the acceleration values in common mode and differential mode $\ddot{x}_{com}^{res}$ and $\ddot{x}_{dif}^{res}$ are expressed by Hadamard matrix $\boldsymbol{H}_2$ as (15)

$$\begin{bmatrix} \ddot{x}_{com}^{res} \\ \ddot{x}_{dif}^{res} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \cdot \begin{bmatrix} \ddot{x}_s \\ \ddot{x}_m \end{bmatrix} = \boldsymbol{H}_2 \begin{bmatrix} \ddot{x}_s \\ \ddot{x}_m \end{bmatrix}. \tag{15}$$

The reference values of acceleration in master and slave systems $\ddot{x}_m^{ref}$ and $\ddot{x}_s^{ref}$ are expressed by inverse of the second order Hadamard matrix $\boldsymbol{H}_2^{-1}$ as (16)

$$\begin{bmatrix} \ddot{x}_m^{ref} \\ \ddot{x}_s^{ref} \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \ddot{x}_{com}^{ref} \\ \ddot{x}_{dif}^{ref} \end{bmatrix} = \boldsymbol{H}_2^{-1} \begin{bmatrix} \ddot{x}_{com}^{ref} \\ \ddot{x}_{dif}^{ref} \end{bmatrix}. \tag{16}$$

Figure 6 shows the block diagram of the abstraction mode.

In bilateral control, action force by the operator and reaction force from the environment are applied to the actuator as disturbance force. Then, disturbance forces F_{dism} and F_{diss} are estimated by disturbance observer as (17) and (18)

$$\hat{F}_{dism} = \frac{g_{dis}}{s + g_{dis}}(F_m + {}^*F_{dism}) \tag{17}$$

$$\hat{F}_{diss} = \frac{g_{dis}}{s + g_{dis}}(F_s + {}^*F_{diss}) \tag{18}$$

where

$${}^*F_{dis} = F_{int} + F_C + D\dot{x}. \tag{19}$$

Only the action force by the operator F_m and reaction force from the environment F_s are estimated by the disturbance observer as (1)–(3).

Therefore, acceleration responses $\ddot{x}_m$ and $\ddot{x}_s$ are derived from (4) as (20) and (21)

$$\ddot{x}_m = \frac{1}{M_n}\hat{F}_m \tag{20}$$

$$\ddot{x}_s = \frac{1}{M_n}\hat{F}_s. \tag{21}$$

Thus, in bilateral control system, the response values of acceleration are obtained by the disturbance observer instead of the force sensors in this paper.

3 RECONSTRUCTION MODE

A. Model of the Environment

Reaction force from the environment is discussed in this subsection. The environment is represented as a spring and damper model. And the model of the environment is shown in Figure 7.

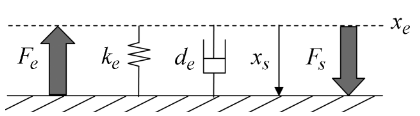


Fig. 7 Modeling of the environment

Reaction force from the environment F_s is derived as (22)

$$F_s = k_e(x_s - x_e) + d_e(\dot{x}_s - \dot{x}_e) = F_k + F_d. \tag{22}$$

Here, the environmental impedance is composed of the stiffness k_e and the viscosity d_e. F_k means the force from the spring and F_d means the force from the damper.

Therefore, it is able to identify the environment and to calculate the environmental impedance from the environmental model.

B. Reconstruction of the environmental impedance

The environmental impedance Z_e is represented by the stiffness k_e and the viscosity d_e. When the operator manipulates the master system and the slave system compress the environment, the operator is able to feel the changes of environmental impedance. In the experiments, the environmental impedance is calculated as a discrete-time modeling. The position response of the system is also obtained. So, the relationship between the environmental impedance and the compression depth is able to be approximated.

An example of abstracted environmental impedance is shown in Figure 8. Then, the impedance k_e and d_e are represented as (23) and (24)

$$k_e = f_{(x)} \tag{23}$$

$$d_e = g_{(x)}. \tag{24}$$

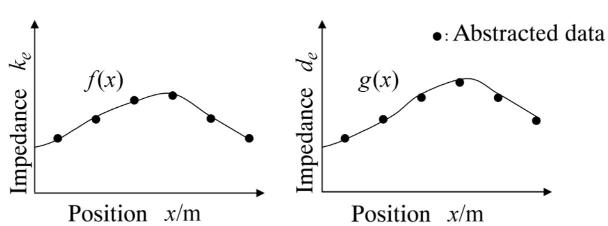


Fig. 8 An example of the abstracted environmental impedance

Here, x means the compression depth of the environment. And, f_x means the function which shows the relationship between the stiffness k_e and the compression depth x. g_x means the function which shows the relationship between the viscosity d_e and the compression depth x. Then, (22) is derived as (25)

$$F_s = F_k + F_d = f_{(x)}(x_s - x_e) + g_{(x)}(\dot{x}_s - \dot{x}_e). \quad (25)$$

From these equations, the relationship between the environmental impedance and the position how deep slave system pushes the environment is able to be attained, and it is also able to be approximated. In this paper, the stiffness k_e is approximated as exponential function of position as (26)

$$k_e = f_{(x)} = Ae^{Bx} + C. \quad (26)$$

And, in this paper, the viscosity d_e is approximated as multi degrees function of position as (27)

$$d_e = g_{(x)} = Ax^3 + Bx^2 + Cx + D \quad (27)$$

where, A, B, C and D mean real numbers.

In consequence, the environment based on the obtained data in abstraction mode is reconstructed in the reconstruction mode.

4 REPRODUCTION MODE

The real environmental impedance is abstracted and reconstructed in the abstraction mode and the reconstruction mode. Then, in the reproduction mode, the force sensation is reproduced based on the reconstructed impedance. The operator manipulates the only master system, and he feels the force sensation reproduced by FSR. Figure 9 shows the block diagram of reproduction mode. In the reproduction mode, the reference value of acceleration in master system $\ddot{x}_m^{ref}$ is represented as (28)

$$\ddot{x}_m^{ref} = C_f(\ddot{x}_{com}^{cmd} - \ddot{x}_{com}^{res}). \quad (28)$$

Then, the reference value of acceleration times nominal mass M_n equals to the form of force as (29)

$$F_m^{ref} = \ddot{x}_m^{ref} M_n. \quad (29)$$

The reaction force from the environment is reproduced by the reconstructed environmental impedance $\hat{Z}_e$ as (30)

$$F_s = F_m^{ref} \frac{1}{M_n s^2} \hat{Z}_e = x_m \hat{Z}_e. \quad (30)$$

Finally, the acceleration which is estimated by disturbance observer $\ddot{x}_m$ is added to the acceleration $\ddot{x}_s$ which is estimated being based on reaction force from the reconstructed real environment as (31)

$$\ddot{x}_{com}^{res} = \ddot{x}_m + \ddot{x}_s = \frac{1}{M_n} \cdot \frac{g_{reac}}{s + g_{reac}} (F_m + F_s). \quad (31)$$

So, the operator feels the force sensation from the reconstructed environment as if he is contacting the real environment right at this very moment through the master-slave system.

5 EXPERIMENTS

A. Experimental Setup

The experimental system in this paper is shown in Figure 10. This system is the forceps robot which has one degree of freedom, and is composed of master system and slave system. A linear motor which is a rod type is implemented as an actuator of both master system and slave system. The human operates the handle of the master system directly, and the forceps of the slave system grips the ob-

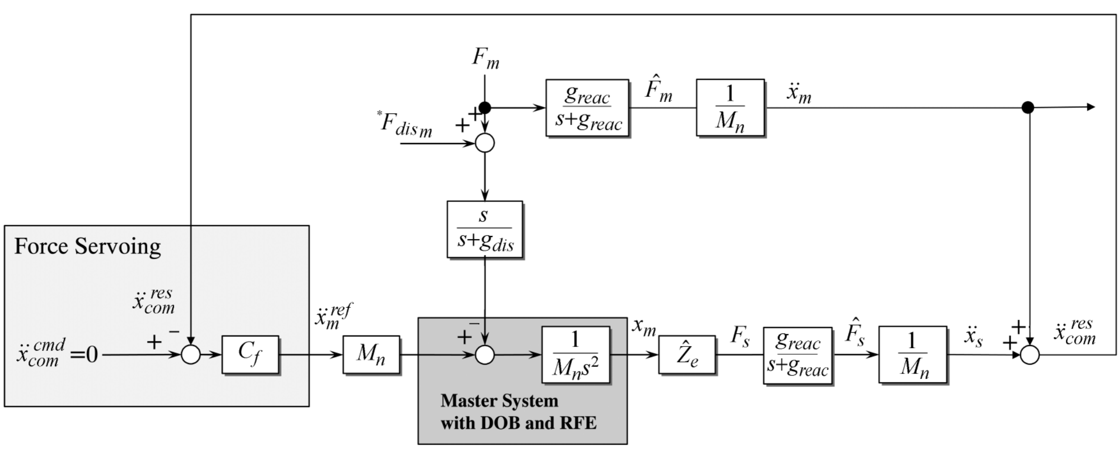


Fig. 9 Reproduction mode

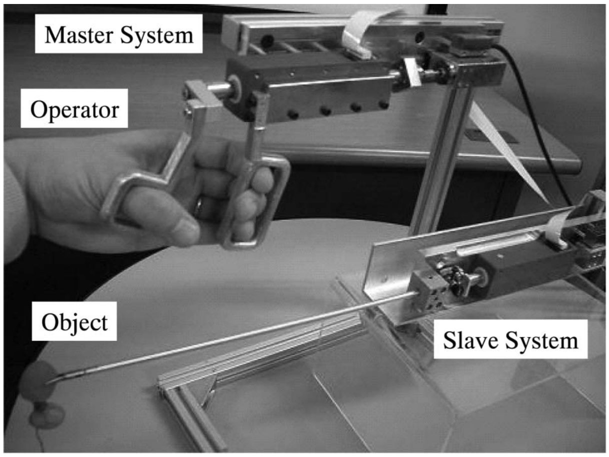


Fig. 10 Force sensation recorder system

ject. The control software for this system is written in C language under RT-Linux. The sampling time is 0.1 ms. In the experiments, the initial position of the tip of the slave system is set on the surface of the objects. The experimental parameters are shown in Table 2.

Table 2 **Experimental Parameters**

Parameter	Description	Value
K_p	Position gain	2500
K_v	Velocity gain	100
K_a	Acceleration gain	1.0
K_f	Force gain	1.0
K_{tn}	Force coefficient	10.832 N/A
M_n	Mass	0.10 kg
g_{dis}, g_{reac}	Cut-off frequency of disturbance observer	500 rad/s

B. Experimental Results

In this paper, the experiments are made on rubber and steel as the real environment. In bilateral control, the input into the system is the force input from the external. However, if human inputs the force into the system, it is impossible to make the same input force in the reproduction mode as the one in the abstraction mode. Therefore, in this paper, the force is applied as ramp function from 3.0 N to 7.0 N as input force to the system.

The experimental results on rubber are shown in Figure 11. The experimental results on steel are shown in Figure 12. From Figure 11(a), (c) and Figure 12(a), (c), slave system almost perfectly tracks master system. It turns out that bilateral control is done perfectly. Especially in the experiments on steel, although the slave robot contacts with hard environment, stable contact motion is realized.

In the abstraction mode, the dynamic parameters of the environmental impedance are abstracted as Figure 11(e), (g) and Figure 12 (e), (g). Then, the relationship between the environmental impedance and the position how deep the slave system pushes the environment is attained as Figure 11(f), (h) and Figure 12(f), (h). From the results, the impedance of the rubber is approximated and reconstructed as

$$k_e = 1.76963 e^{8193.37x} + 6865.72 \tag{32}$$

$$d_e = -1.15244 \times 10^{12} x^3 + 1.80253 \times 10^9 x^2 - \\ - 877151x + 129.459. \tag{33}$$

On the other hand, the impedance of the steel is approximated and reconstructed as

$$k_e = 0.0249844 e^{61736.2x} + 4339.32 \tag{34}$$

$$d_e = -7.3079 \times 10^9 x^3 + 2.12005 \times 10^{10} x^2 - \\ -8.61603 \times 10^6 x + 871.809. \tag{35}$$

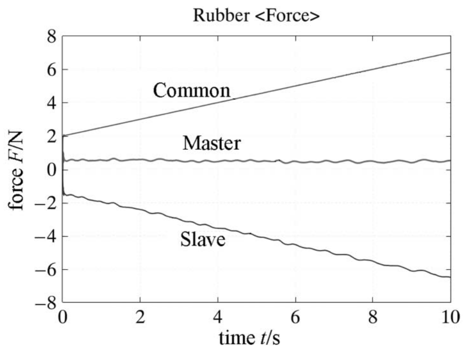
Then, these approximated curve functions of environmental impedance are used for the experiments in the reproduction mode.

The experimental results on rubber in the reproduction mode are shown in Figure 11(b), (d). And, the experimental results on steel in the reproduction mode are shown in Figure 12(b), (d). From these experimental results, it turns out that the relationship between the operational force and the position deviation is equal to one in the abstraction mode. So, the real environment is reconstructed precisely. It also can be said that the force sensation from the real environment is reproduced perfectly.

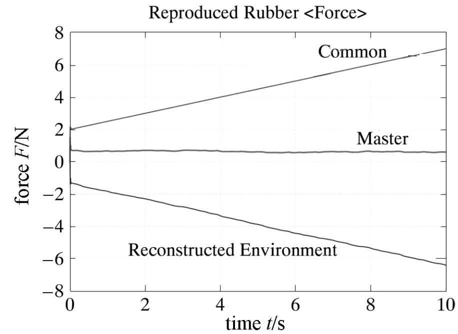
Furthermore, the system transmits the force information with 79.6 Hz of bandwidth because of the cut-off frequency of disturbance observer which is set as 500 rad/s. Since the system has high bandwidth, human feels vivid force sensation of the environment. Since the environment is abstracted as a bilateral database, human feels the reaction force as if from the real environment.

6 CONCLUSIONS

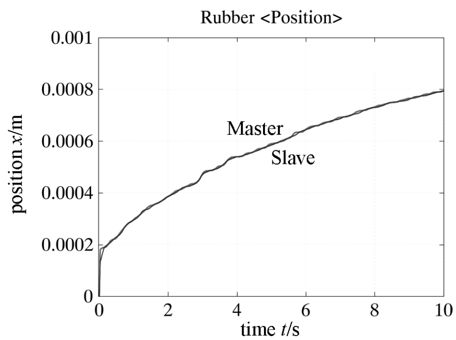
This paper proposed the novel bilateral control architecture which was able to transmit vivid force sensation. The new conception and new system of force sensation recorder (FSR) system were also proposed. The proposed FSR system had three modes. Three modes were the abstraction mode, the reconstruction mode, and the reproduction mode. In the abstraction mode, a master-slave system was composed and the law of action and re-



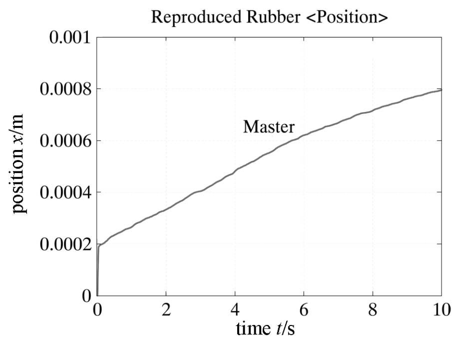
(a) Force responses (Abstracted rubber)



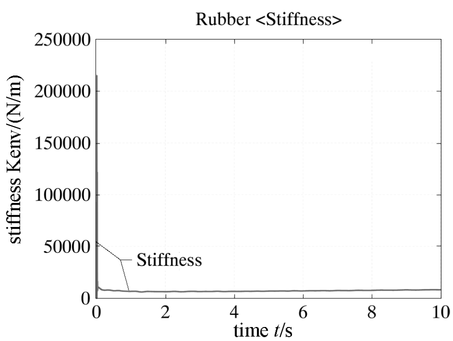
(b) Force responses (Reproduced rubber)



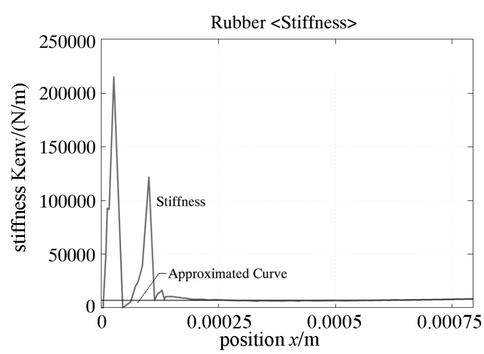
(c) Position responses (Abstracted rubber)



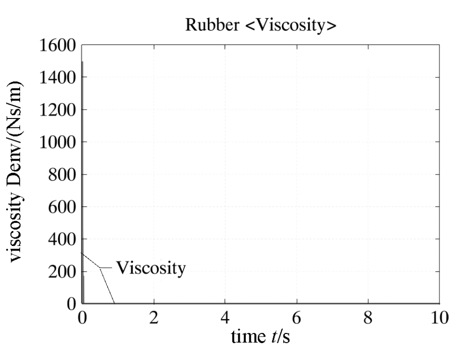
(d) Position responses (Reproduced rubber)



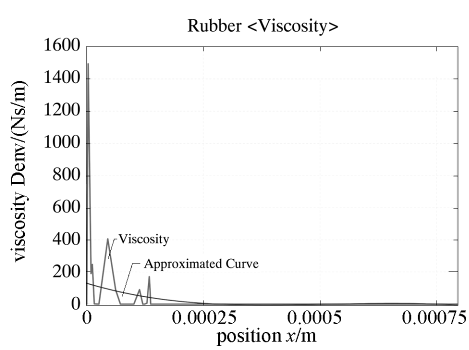
(e) Stiffness responses (Abstracted rubber)



(f) Stiffness responses (Approximated curve)

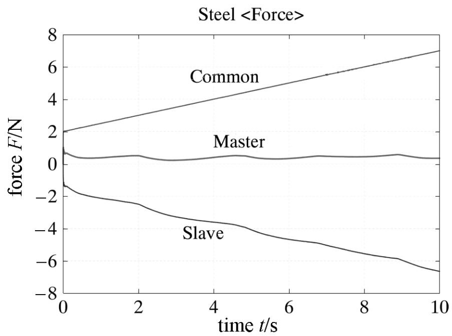


(g) Viscosity responses (Abstracted rubber)

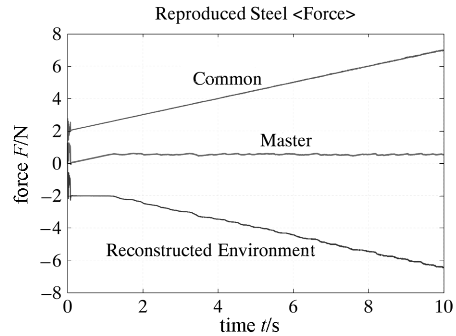


(h) Viscosity responses (Approximated curve)

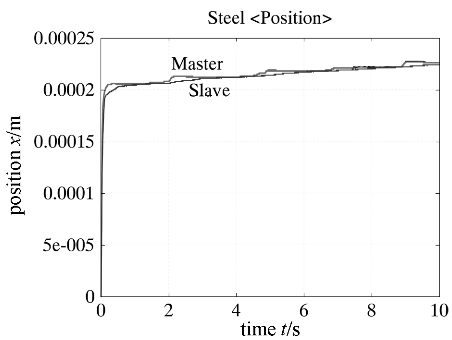
Fig. 11 Experimental results (rubber)



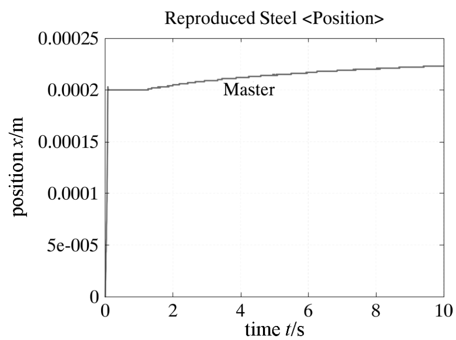
(a) Force responses (Abstracted steel)



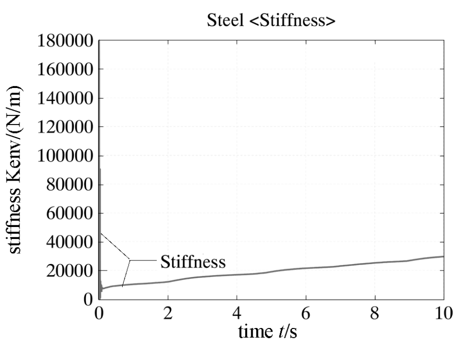
(b) Force responses (Reproduced steel)



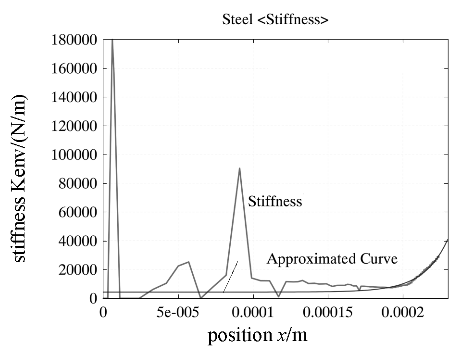
(c) Position responses (Abstracted steel)



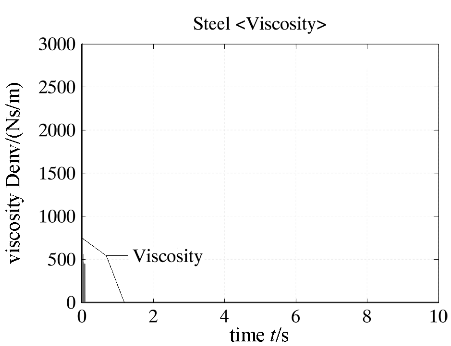
(d) Position responses (Reproduced steel)



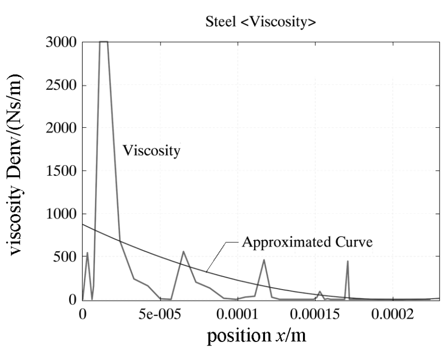
(e) Stiffness responses (Abstracted steel)



(f) Stiffness responses (Approximated curve)



(g) Viscosity responses (Abstracted steel)



(h) Viscosity responses (Approximated curve)

Fig. 12 Experimental results (steel)

action was attained by bilateral control artificially. Then, the force sensation information was abstracted from the real environment. Later, in the reconstruction mode, the force sensation information was reconstructed by proposed environmental modeling method based on the stiffness and viscosity. Later, in the reproduction mode, human operator manipulated the only master system and felt force sensation from the environmental model which was reconstructed in the reconstruction mode. The experimental results showed the viability of the proposed method. The proposed force sensation acquisition system based on bilateral control will be a fundamental technology for evolution of haptic database.

ACKNOWLEDGEMENTS

This research was supported in part by the Ministry of Education, Culture, Sports, Science and Technology of Japan under Grant-in-Aid for Scientific Research (A), 17206027, 2005.

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Bilateralno upravljanje gibanjem za apstrakciju i reprodukciju stvarne sile. Održavanje sposobnosti iskusnih operatera i uvježbavanje novih operatera postaje sve važnijim zadatkom u medicinskim i proizvodnim primjenama. Nove operatere najbolje uvježbavaju iskusni operateri, ali njih sve više nedostaje. Inovativno rješenje toga problema može biti pohranjivanje vještina iskusnih operatera u tzv. haptičku bazu podataka. U ovome se članku za razvoj haptičke baze podataka predlažu metode apstrakcije i reprodukcije stvarne sile u bilateralnom upravljanju te metoda rekonstrukcije udaljenoga stvarnoga prostora u kojemu djeluje prateći sustav. U apstrakcijskom načinu rada uspostavlja se bilateralno upravljanje između vodećeg i pratećeg sustava uz održavanje zakona akcije i reakcije između njih. Nakon toga estimiraju se sila, brzina i pozicija vodećeg i pratećeg sustava na temelju informacije o ubrzanju. U rekonstrukcijskom načinu rada rekonstruira se model udaljenoga stvarnoga prostora na osnovi podataka iz stvarnoga udaljenoga prostora. Na koncu, primjenom reprodukcijskog načina rada na strani vodećeg sustava operater bi trebao osjećati silu iz modela udaljenog prostora izgrađenog u rekonstrukcijskom načinu rada. Predloženi sustav omogućuje spremanje bilateralno prenošene sile u bazu podataka, što je potkrijepljeno eksperimentalnim rezultatima.

Ključne riječi: bilateralno upravljanje gibanjem, haptičko sučelje, haptička baza podataka, osjećaj stvarne sile

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Received: 2005-12-01