A Controller Design Method of Bilateral Control System

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Abstract— **Haptic sense is indispensable for skillful operation in a telerobotic system. Bilateral control attracts considerable interest because it transfers the haptic sense to a remote place. Although it is simply composed of two manipulators, its design is complicated. This study proposes an idea that provides a new framework on design of a bilateral control system. The idea is to design the bilateral control system based on a "function", a minimum component of a system role. It enables simple and explicit design for various tasks. The features of the proposed method provide a way to design an adjustable system. Experimental results show the validity of the proposed method.**

Key Words: **Bilateral control, force control, disturbance observer, teleoperation**

I. Introduction

Bilateral control is a method for a robotic teleoperation system. It is superior in the respect that it transfers haptic sense to a remote place. Hence it has been studied for a long time to carry out a skilled operation in the remote place. Although it is simply composed of two manipulators, its design is complicated. Many types of controllers such as position-position, position-force, force-position and force-force architectures were investigated. Lawrence[1] utilized "four-channel" architecture that shows general structure of bilateral control systems. Modal decomposition methods simplify the design of the bilateral control system[2], [3], [4]. Although many types of bilateral control systems exist, many new architectures are still investigated.

At the same time, promising indices have also been proposed. Yokokohji and Yoshikawa defined an ideal response of the bilateral control system in [5]. Hannaford specified this response with the hybrid matrix[6]. The condition of "transparency", another concept of an ideal response, is evaluated using the hybrid matrix[1]. Our research group proposed indices of "reproducibility" and "operationality", which give quantitative evaluation[7]. The ideal response is divided into two independent features evaluated by the indices.

Most of previous studies on bilateral control aimed at acquisition of transparency. Ideally, such a system can be represented by an infinitely stiff and weightless mechanical connection between the end-effectors of the master arm and the slave arm[8]. In order to actualize it by control, high feedback gains in both position and force control is required. However, it is indicated in [8] that the highest level of force feedback is not universally beneficial. Lee and Li presented an interesting design method for a bilateral control system to behave as a common passive rigid mechanical tool[4]. The study infer that the teleoperator should appear to the human as a mechanical extension of his/her body.

In sum, the main goal of this study is an adjustable bilateral control system instead of the ideal system. Here, the adjustable system means a control system that allows the following arrangement.

- modification of its apparent mechanical parameters
- dynamical task shift

An idea of functionality is proposed as a new design framework for an adjustable bilateral control system. Simplicity and explicitness of the proposed framework provide a way to design the adjustable system.

Contents of this paper are as follows: The idea of functionality is proposed in Section II. This study introduces coordinate transformation to associate functions with robots. The coordinate transformation method is described in Section III. Section IV shows examples of controller design and indicates some features of the method. Experimental results are shown in Section V. Finally this paper is concluded in Section VI.

II. Definition of function

Functionality is an idea for design of a bilateral control system. At first, the system role is defined as follows:

Definition 1 "System role" is a description of the requirement from a user to a robot control system.

The control system should be designed to satisfy this system role. It is, however, difficult to directly associate a system role with a controller since the system role consists of abstract words. The idea of functionality is introduced as follows to concretize the system role.

Definition 2 "Function" is a minimum component of a system role. Conversely, the system role is described as a combination of functions.

In this study, a bilateral control system is designed based on functions. Fig. 1a shows a design framework of conventional bilateral control systems. In conventional methods, a controller directly corresponds to a manipulator. The two controllers receive their command values from a command generator. The command generator, which determines the type and the feature of the control system, should be designed so as to meet the system role. However, the behavior of the total system is hardly analogized from the structure of the command generator. Its design depends on the empirical knowledge of the designer since there is no explicit procedure to decide the architecture. Unclear correspondence between the controllers and the system role leads to the difficulty of design.

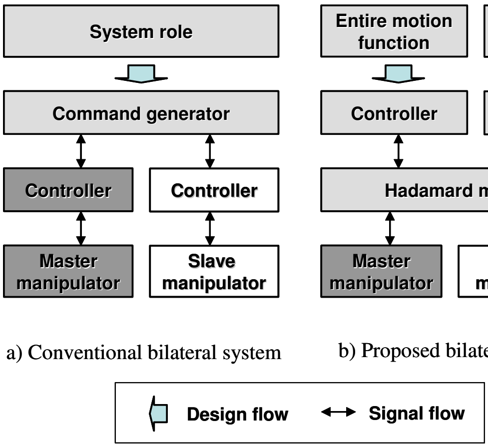

Fig. 1. Design framework of bilateral system

Hence we propose a design framework shown in Fig. 1b. The system role is divided into functions. Controllers are designed to satisfy individual functions.

There are two categories of functions in the bilateral control system. One is a function of coupling and the other is a function of entire motion.

It is able to control master and slave manipulators as if they are coupled with a spring. It is also able to realize a rigid coupling with a controller. This kind of parts that a controller plays will be treated as a function. We define these parts as a spring coupling function and a rigid coupling function respectively. These functions are classified as coupling functions.

Meanwhile, functions to control the entire motion exist when master and slave manipulators are treated as a coupled system. The friction effect could be compensated if an accurate friction model is derived. This is defined as a friction compensation function. It is also able to manipulate the apparent inertia of the entire system with a controller. This is defined as an inertia manipulation function. These functions are classified as entire motion functions.

These functions could be realized by control while some of these functions are also achievable with mechanical tools. In each case, they are treated as same functions. The examples of functions are shown in Fig. 2.

Coupling functions are accomplished by controlling the position gap of the two manipulators, master and slave. At the same time, entire motion functions relate to the sum of the two manipulator positions. Consequently, coordinate transformation should be applied to design the controller based on functions.

III. Coordinate Transformation

In order to design the controllers based on functions, the robot coordinate should be transformed to a new

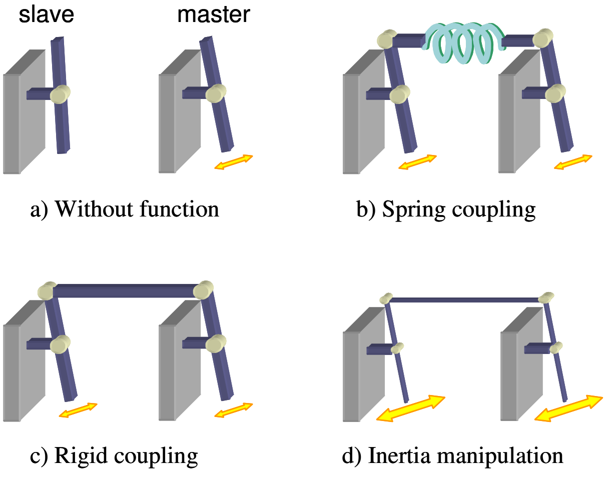

Fig. 2. Examples of functions

coordinate based on functions. Here, the coordinates based on the information of each control object is defined as a robot coordinate. On the other hand, the transformed coordinate based on the information of functions is defined as a function coordinate. An Hadamard matrix is useful for the transformation on a bilateral control system[9]. It transforms each variable into common and differential modes, which relate to the functions. In other word, this coordinate transformation performs modal decomposition. Coordinate transformation is figured out from (1).

$$\begin{bmatrix} x_+ \\ x_- \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}\begin{bmatrix} x_m \\ x_s \end{bmatrix} = \frac{1}{2}\boldsymbol{H}_2\begin{bmatrix} x_m \\ x_s \end{bmatrix} \quad (1)$$

where the subscript m denotes the master manipulator, the subscript s denotes the slave manipulator, the subscript + denotes the common coordinate and the subscript − denotes the differential coordinate. x shows the position of a manipulator. $\boldsymbol{H}_2$ is the quadratic Hadamard matrix.

In this paper, kinematics and dynamics of master and slave manipulators are considered in 1 DOF for simplicity.

x_m and x_s are defined as a robot coordinate system. x_+ and x_- are defined as a function coordinate system.

Velocity and force are also transformed with the Hadamard matrix as follows:

$$\begin{bmatrix} \dot{x}_+ \\ \dot{x}_- \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}\begin{bmatrix} \dot{x}_m \\ \dot{x}_s \end{bmatrix} = \frac{1}{2}\boldsymbol{H}_2\begin{bmatrix} \dot{x}_m \\ \dot{x}_s \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} f_+ \\ f_- \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}\begin{bmatrix} f_m \\ f_s \end{bmatrix} = \boldsymbol{H}_2\begin{bmatrix} f_m \\ f_s \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} \tau_+ \\ \tau_- \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}\begin{bmatrix} \tau_m \\ \tau_s \end{bmatrix} = \boldsymbol{H}_2\begin{bmatrix} \tau_m \\ \tau_s \end{bmatrix} \quad (4)$$

where f denotes external force given to the manipulator and τ denotes input force.

Fig. 3 shows the transformation by a block diagram. With the Hadamard matrix, a position plain on robot coordinates is transformed to a position plain on function coordinates. Now, derivation of dynamic equations on function coordinates is described.

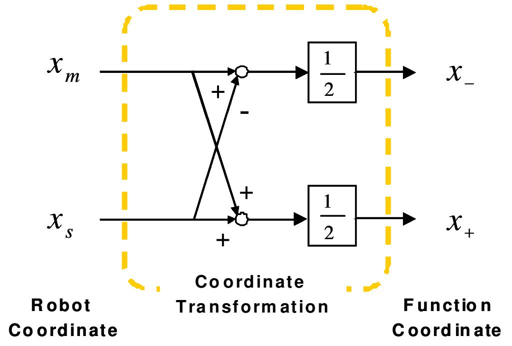

Fig. 3. Coordinate transformation

At first, the dynamic equations on the robot coordinates are shown as follows:

$$M_m\ddot{x}_m + \mu_m\dot{x}_m = \tau_m + f_m \quad (5)$$
$$M_s\ddot{x}_s + \mu_s\dot{x}_s = \tau_s + f_s \quad (6)$$

here, M denotes mass of the manipulator and μ denotes the friction coefficient.

Assuming that the models of master and slave manipulators are equivalent, sum and difference of (5) and (6) are figured out as follows:

$$M_t\cdot\frac{1}{2}(\ddot{x}_m+\ddot{x}_s)+\mu_t\cdot\frac{1}{2}(\dot{x}_m+\dot{x}_s) = (\tau_m+\tau_s)+(f_m+f_s) \quad (7)$$
$$M_t\cdot\frac{1}{2}(\ddot{x}_m-\ddot{x}_s)+\mu_t\cdot\frac{1}{2}(\dot{x}_m-\dot{x}_s) = (\tau_m-\tau_s)+(f_m-f_s) \quad (8)$$

here, $M_t = M_m + M_s$ and $\mu_t = \mu_m + \mu_s$. Then, the dynamic equations in function coordinates are derived as follows:

$$M_t\ddot{x}_+ + \mu_t\dot{x}_+ = \tau_+ + f_+ \quad (9)$$
$$M_t\ddot{x}_- + \mu_t\dot{x}_- = \tau_- + f_-. \quad (10)$$

It is shown from (9) and (10) that dynamics on common and differential coordinates could be treated the same as two independent physical systems. It is reasonable to add inputs from the controllers in the function coordinate system to the manipulators in the robot coordinate system since the inputs are independent in transformed position plain. Hence the controller design on individual function coordinates is independent to each other.

IV. Controller Design

In this section, some examples of a function-based controller design method are described. Then features of the design method are indicated.

Fig. 4 shows the first example. A PD controller is mounted in the differential coordinate. The force input from the PD controller is figured out as follows:

$$\tau_- = -K_-x_- - D_-\dot{x}_-. \quad (11)$$

Substituting (11) to (10),

$$M_t\ddot{x}_- + \mu_t\dot{x}_- = f_- - K_-x_- - D_-\dot{x}_-$$
$$M_t\ddot{x}_- + (D_- + \mu_t)\dot{x}_- + K_-x_- = f_-. \quad (12)$$

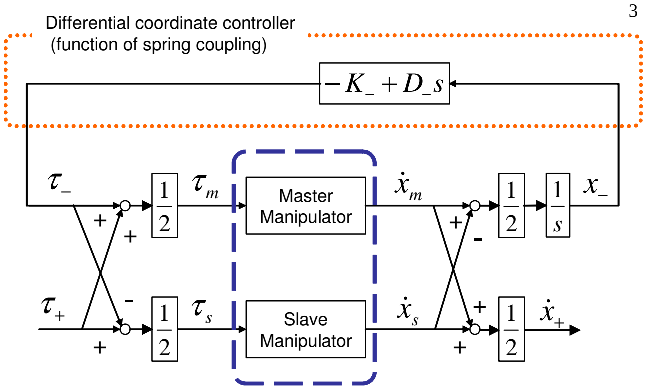

Fig. 4. Spring coupling

As shown in (12), PD controller works the same as a mechanical spring with stiffness K_- and viscosity D_-. Hence this controller serves as a spring coupling function.

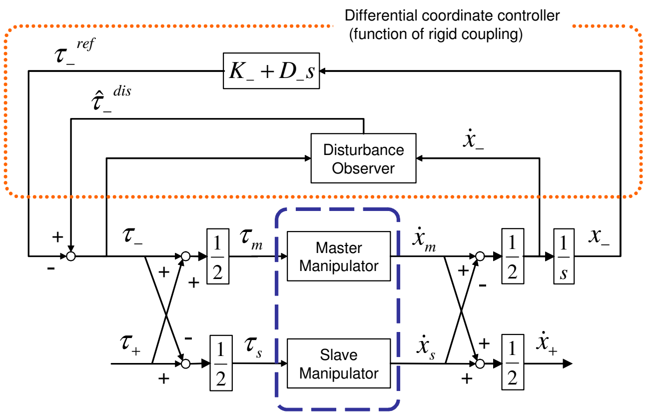

Fig. 5. Rigid coupling

Fig. 5 shows a PD controller with disturbance observer[10] in the differential coordinate. This controller realizes a rigid coupling function. The disturbance observer in the differential coordinate is composed as shown in Fig. 6.

Here, g denotes the cutoff frequency of the disturbance observer.

The input torque of this control system is figured out as follows:

$$\tau_- = -(K_- + D_-s)x_- - \frac{g}{s+g}(f_- - \mu_t\dot{x}_-). \quad (13)$$

Substituting (13) to (10),

$$M_t\ddot{x}_- + D_-\dot{x}_- + K_-x_- = \frac{s}{s+g}(f_- - \mu_t\dot{x}_-). \quad (14)$$

In low frequency range, every kind of disturbance including external force is completely canceled. Therefore, this function of coupling works as a rigid coupling. Since x_-, the gap of two manipulators, rapidly converges to zero and it would not be interfered with any other disturbances, it is reasonable to assume that stiffness of the function is infinity in the frequency range lower than the cutoff

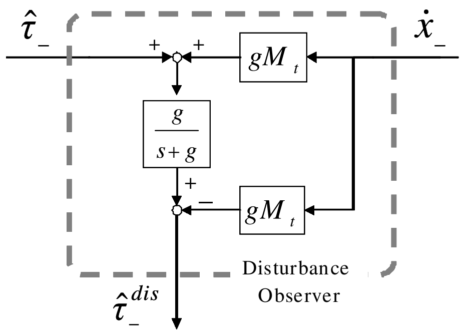

Fig. 6. Disturbance observer in differential coordinate

frequency of disturbance observer. At the same time, this function works as a spring coupling function in the higher frequency range since disturbance observer would not sense the disturbances in the high frequency range.

In the controllers shown above, there is no torque input in the common coordinate. This means no control is applied to common coordinate motion and both manipulators will move freely as the external force affects either manipulator.

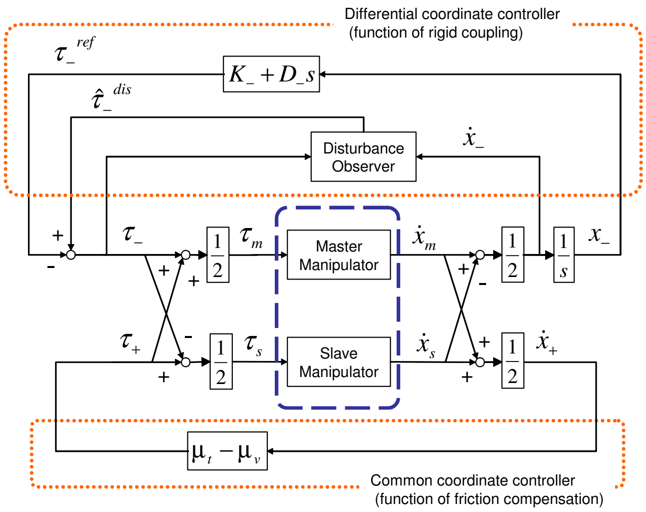

Fig. 7. Friction compensation

Fig. 7 shows a controller based on a function of friction compensation. The controller in the differential coordinate works as a rigid coupling function. Sum of the friction torque is estimated and feedback input is given in the common coordinate.

Substituting $\tau_+ = (\mu_t - \mu_v)\dot{x}_+$ to (9),

$$M_t \ddot{x}_+ + \mu_v \dot{x}_+ = f_+ \tag{15}$$

here, μ_v is the virtual friction coefficient.

(15) shows that the apparent friction coefficient is arbitrarily configured. For example, if the friction estimation is accurate and $\mu_v = 0$ is given, both manipulators move passively as if no friction occurs on the joint. Note, however, that static friction remains in practice.

Fig. 8 shows a controller based on a function of inertia manipulation. External force f_m and f_s is measured by

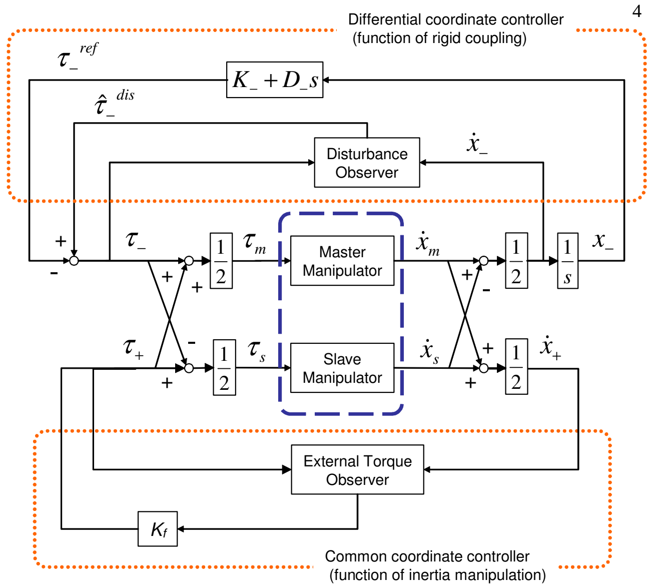

Fig. 8. Inertia manipulation

external torque observer (ETOB) [10] in the common coordinate. τ_+, input force in the common coordinate, is figured out as follows:

$$\tau_+ = K_f f_+. \tag{16}$$

Substituting (16) to (9),

$$\begin{aligned} M_t \ddot{x}_+ + \mu_t \dot{x}_+ &= (1 + K_f) f_+ \\ \frac{M_t}{1+K_f}\ddot{x}_+ + \frac{\mu_t}{1+K_f}\dot{x}_+ &= f_+ \\ M_v \ddot{x}_+ + \mu_v \dot{x}_+ &= f_+ \\ M_v = \frac{M_t}{1+K_f} & \\ \mu_v = \frac{\mu_t}{1+K_f}. & \end{aligned} \tag{17}$$

here M_v denotes virtual mass realized by the inertia manipulation function.

As force feedback gain K_f becomes larger, virtual mass becomes smaller. Additionally, the virtual friction coefficient also becomes smaller. The inertia manipulation function interferes with the function of friction compensation since both functions exist in the same coordinate. This fact indicates that multiple functions in a coordinate should be designed as a combined system.

Fig. 9 shows a controller based on a position limit function. PD controller in the common coordinate works when the manipulators exceed a position limit. It pushes the manipulators back to the limit position. In other words, it represents a mechanical stopper with stiffness K_+ and viscosity D_+.

Some other functions such as a function for gravity compensation and a function for velocity limit may also be required in some situations. Hence many kinds of functions are applicable. Additionally, any control scheme could be applicable to realize a function. In sum, the framework of

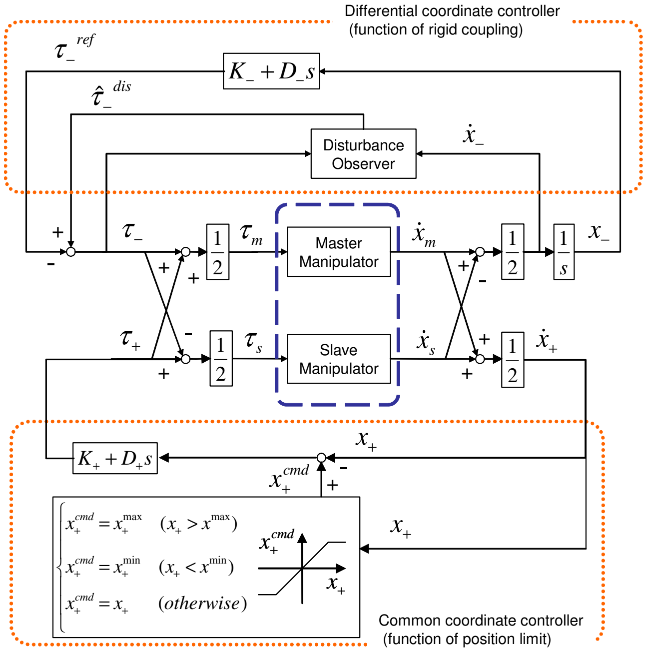

Fig. 9. Position limit

functionality deals with various architectures and various control schemes.

These examples of controllers show the simplicity and the explicitness of function-based controller design. Since a function is a minimum component, characteristics of the function are simple. Functions in different coordinates are completely independent to each other. Only when multiple functions exist in one coordinate, the interference of functions in the coordinate should be considered. The design problem is explicit since individual controllers correspond to each function without any interference of functions in the other coordinate.

The simplicity and the explicitness provide a way to design an adjustable system. The functions represent apparent mechanical properties such as inertia of the manipulator, friction of the manipulator, stiffness of a stopper and stiffness of a coupling. These properties are realized with the controllers designed in a simple and explicit way. Furthermore, task shifts is easily executed with this method. In case of the task shifts, conventional methods require redesign of the entire system while individual functions are easily mounted and unmounted in this method. The design problem is localized in individual function coordinates. It is to be noted that the designer has to consider transient characteristics and smoothness of command values at the moment of task shift.

The framework in this study is based on the idea of modal decomposition. The modal decomposition method is already applied to some control systems such as mobile robots including wheel chairs[11], twin drive systems[9] and flywheels. The framework is also applicable to them while this paper only deals with a bilateral control system.

V. Experiment

A. Description of experimental system

The overview of the bilateral control system is shown in Fig. 10. This experimental system is composed of two equivalent 1DOF manipulators connected to a PC through motor drivers. The parameters of manipulators are shown in Table I. Gravity term is negligible since the rotational plane of the manipulator is horizontal. The control parameters are shown in Table II.

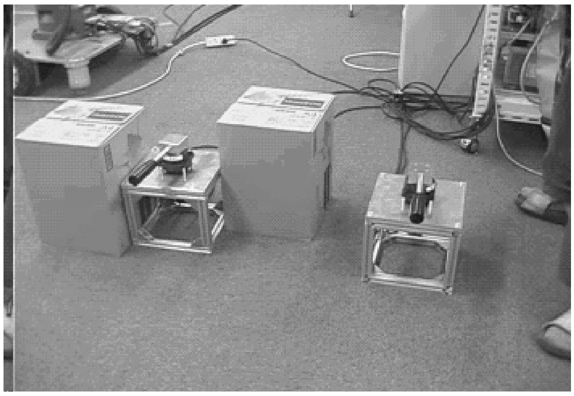

Fig. 10. Experimental system

TABLE I
Manipulator Parameters

Arm length	$[m]$	0.16
Rated power output	$[W]$	50
Rated motor torque	$[mNm]$	159.0
Reduction ratio		1/33
Number of encoder pulse	$[P/R]$	2048
MOI at reducer output shaft	$[kgm^2]$	0.00535

TABLE II
Control Parameters

	Sampling time	$[ms]$	0.1
g	Cutoff frequency of DOB	$[rad/s]$	1100
g_f	Cutoff frequency of ETOB	$[rad/s]$	700
K_-	Position gain of coupling function		20
D_-	Velocity gain of coupling function		0.8
K_+	Position gain of position limit function		20
D_+	Velocity gain of position limit function		0.8
K_f	Force gain in common coordinate		1.5
x_{max}	Position limit	$[rad]$	0.3

B. Experimental result

Fig. 11 compares positions of the both manipulators while Fig. 12 shows the difference of them. Fig. 13 compares external force of the manipulators. Here, slave force is shown upside-down to compare the force in opposite directions.

Tasks of the bilateral control system were shifted several times during the experiment. The combinations of functions are represented by five stages, from stage 1 to stage 5, as shown in Table. III.

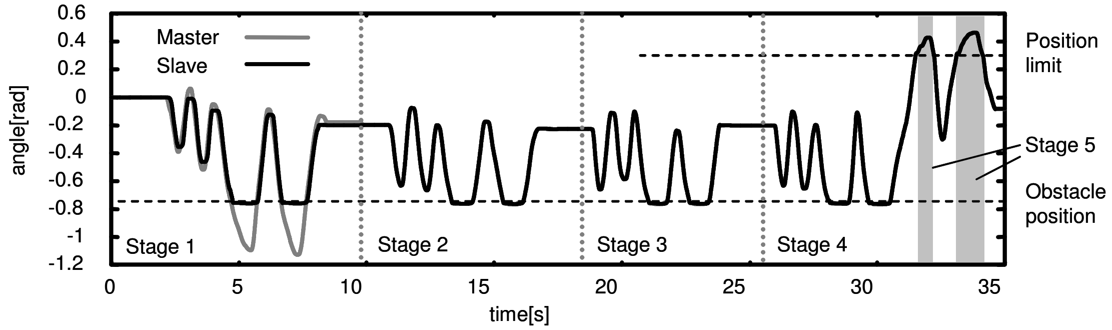

Fig. 11. Position response

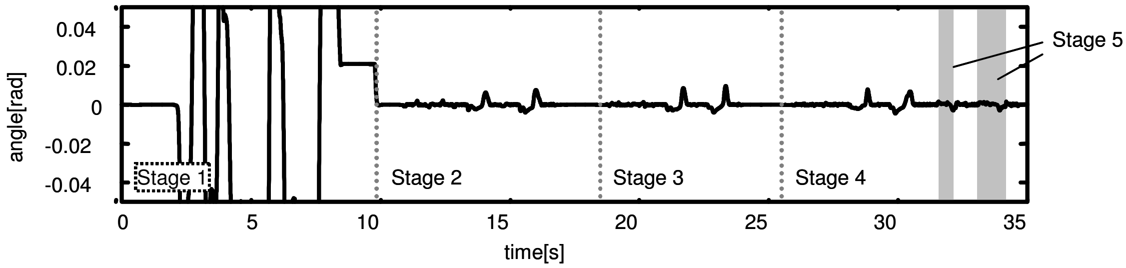

Fig. 12. Difference of position response

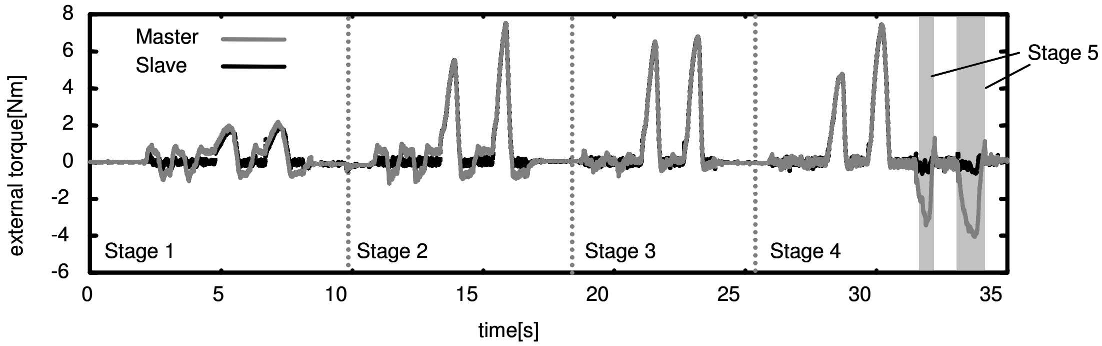

Fig. 13. External force response

TABLE III

FUNCTIONS IN EACH STAGE

	Common coordinate	Differential coordinate
stage 1	none	Spring coupling
stage 2	none	Rigid coupling
stage 3	Friction compensation	Rigid coupling
stage 4	Friction compensation & Inertia manipulation	Rigid coupling
stage 5	Position limit	Rigid coupling

From stage 1 to stage 4 are switched arbitrarily by the operator. On the contrary, stage 5 starts accidentally when the manipulators exceed a position limit. Function-based controller design deals not only with task shifts but also with exception handling.

In each stage, the operator conducted two motions: a free motion and a touching motion. Firstly, he reciprocated the manipulator twice in the free motion. Secondly, he pushed the obstacle twice through the slave manipulator in the touching motion.

During the free motion in stage 1 and 2, the force responses of both manipulators did not accord each other since the master manipulator detected certain amount of force. The force is called manipulation force. It mainly consists of sum friction force and sum inertia force of the two manipulators. Therefore the manipulation force reduced in stage 3, the stage with a friction compensation function. Finally the manipulation force was the smallest in stage 4 since both friction force and inertia force were reduced.

During the touching motion in stage 1, pushing force increased in proportion to the position difference between the both manipulators. It shows that the spring coupling function worked the same as a mechanical spring coupling. During the touching motion in stage 2 to 5, force responses of both manipulators agreed very well. Position responses of both manipulators also agreed very well. These facts show that the rigid coupling function worked the same as a mechanical rigid coupling.

Fig. 12 shows that position difference of both manipulators slightly altered at the moment of contact. The amount of the alteration was about the same in stage 2, 3 and 4 while almost same amount of external force was applied in each stage. In sum, the functions in the common coordinate did not interfere with the rigid coupling function.

VI. Conclusion

This paper proposed an idea of “functionality”, a new framework for a bilateral control system. Its features are summarized as follows:

- Function-based controller design is simple and explicit.
- A function represents an apparent mechanical property of a bilateral control system.
- The decoupled design enables task shifts for various purposes.

Consequently, this framework is well suited for designing an adjustable bilateral system.

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References

[1] D. A. Lawrence, “Stability and Transparency in Bilateral Teleoperation”, IEEE Trans. R & A, Vol. 9, No.5, pp.624–637, 1993

[2] M.Morisawa, T.Tsuji, Y.Nishioka, K.Akuzawa, H.Takahashi and K.Ohnishi, “Contact Motion in Unknown Environment”, Proc. IEEE Int. Conf. Industrial Electronics, Control and Instrumentation (IECON’03), pp. 992–996, 2003

[3] Y.Matsumoto, S.Katsura and K.Ohnishi, “An Analysis and Design of Bilateral Control Based on Disturbance Observer”, IEEE Int. Conf. Industrial Technology (ICIT’03), pp. 802–807, 2003

[4] D. Lee and P.Y. Li, “Passive Bilateral Feedforward Control of Linear Dynamically Similar Teleoperated Manipulators”, IEEE Trans. R & A, Vol. 19, No. 3, pp. 443–456, 2003

[5] Y. Yokokohji and T. Yoshikawa, “Bilateral Control of Master-Slave Manipulators for Ideal Kinesthetic Coupling”, Proc. IEEE Conf. R & A, pp. 849–858, 1992

[6] B. Hannaford, “A Design Framework for Teleoperators with Kinesthetic Feedback”, IEEE Trans. R & A, Vol. 5, No. 4, pp. 426–434, 1989

[7] W. Iida and K. Ohnishi, “Reproducibility and Operationality in Bilateral Teleoperation”, Proc. IEEE Conf. Advanced Motion Control (AMC’04), pp. 217–222, 2004

[8] G. J. Raju, G. C. Verghese and T. B. Sheridan, “Design Issuse in 2-port Networ1k Models of Bilateral Remote Manipulation”, Proc. IEEE Int. Conf. R & A, pp. 1316–1321, 1989

[9] M. Morisawa and K. Ohnishi, “Motion Control Taking Environmental Information Into Account”, EPE journal, Vol. 12, No. 4, pp. 37–41, 2002

[10] K. Ohnishi, M. Shibata, T. Murakami, “Motion Control for Advanced Mechatronics”, IEEE/ASME Trans. on Mechatronics, Vol. 1, No. 1, pp. 56–67, 1996

[11] S. Katsura and K. Ohnishi, “Advanced Motion Control for Wheelchair Based on Environment Quarrier”, IEEJ Trans. Industry Applications, Vol. 125, No. 7, pp. 698–704, 2005

[12] S. Tachi and T. Sakaki, “Impedance Controlled Master Slave Manipulation System Part I: Basic Concept and Application to the System with Time Delay”, Journal of RSJ, Vol. 8, No. 3, pp. 241–252, 1990 (in Japanese)

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