Position/Force Scaling of Function-based Bilateral Control System

Toshiaki Tsuji and Kouhei Ohnishi
Keio University
Department of System Design Engineering
3-14-1, Hiyoshi, Kohoku-ku, Yokohama, Japan
(tsuji,ohnishi)@sum.sd.keio.ac.jp

Abstract— **This paper describes the method of a scaling control for bilateral control systems. We have already suggested the concept of function so that a controller design of decentralized control systems becomes simple and explicit. Our suggestion in this paper is about a position/force scaling control on a function-based bilateral control system. A conventional coordinate transformation is expanded and the idea of scaling matrix is introduced. Independent position and force scaling controls are achieved applying this scaling matrix. We develop the dynamics of manipulators to show that the dynamics in scaled function coordinates are independent to each other. Experimental results show the high transparency bilateral control with the function-based controller on scaled function coordinates.**

Key Words: **Bilateral control, function-based control, scaling control, force control, disturbance observer, teleoperation**

1 Introduction

Bilateral control has been studied for a long time in order to achieve skilled operations in the remote place. Many types of controllers such as position-position architecture, force feedback architecture, force reflecting architecture and parallel architecture were investigated[1]. Lawrence[2] utilized "four-channel" architecture that shows a general structure of bilateral control systems. The problem of these controllers was that the relationship between the architecture and the system role was not clear.

At the same time, promising indices were also suggested. Yokokohji and Yoshikawa defined the ideal response of bilateral control systems in [3]. Hannaford[4] specified this response by hybrid matrix. However, in practice, the system becomes unstable if we try to realize the ideal response. It is able to get close to the ideal response applying an appropriate impedance control to both master and slave manipulators[5]. Unfortunately, this impedance control degrades the transparency. Our research group has suggested indices of "reproducibility" and "operationality" that realize a quantitative evaluation[6]. The issue of the ideal response is divided into two independent features.

Although the composition of bilateral control is very simple and promising indices exist, the controller design is not easy. We have suggested the idea of "function" that is to divide the system role into minimum components[12]. A coordinate transformation is done and controllers are designed based on this "function". Although the controller design became simple and explicit with this method, the variety of the operation was limited. In this paper, a scaling control method for position and force scaling is suggested in order to expand the function-based controller in application. Scaling matrix is introduced for the coordinate transformation. Dynamics of manipulators are developed in order to show that the dynamics in the transformed coordinates are independent to each other. With this, the independent controllers based on functions could be designed on each scaled coordinate.

Contents of this paper are as follows: The idea of function is explained in section 2. Conventional and suggested coordinate transformation methods are described in section 3. An example of controller compositions for transparent scaling control is shown in section 4. Experimental results are shown in section 5 and finally this paper is concluded in section 6.

2 Definition of function

It is much convenient to divide the system role into independent features in order to express a bilateral control system in a clear manner. These independent features are called "function". The idea of "function" is defined as follows[12].

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

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

It is able to control as if two manipulators are coupled with a spring. It is also able to realize a rigid coupling with a bilateral controller. These kinds of

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roles that controllers play will be treated as functions. We define these roles as spring coupling function and rigid coupling function respectively. These functions are classified to coupling functions.

Meanwhile, functions to control the entire motion exist when master and slave manipulators are treated as one coupled system. It is able to compensate the friction effect if an accurate friction model is derived. This is defined as friction compensation function. It is able to manipulate the virtual inertia of the entire system with a controller. This is defined as inertia manipulation function. The function to bring back the entire system to the initial position is also available. These are classified to entire motion functions.

Controllers are designed so as to achieve these functions. Some of these functions are also achievable with mechanical tools. In each case, they are treated as same functions. This shows that the idea of function realizes a unified expression for both mechanical systems and control systems. The examples of functions are shown in Fig.1. Details of these examples are described in [12].

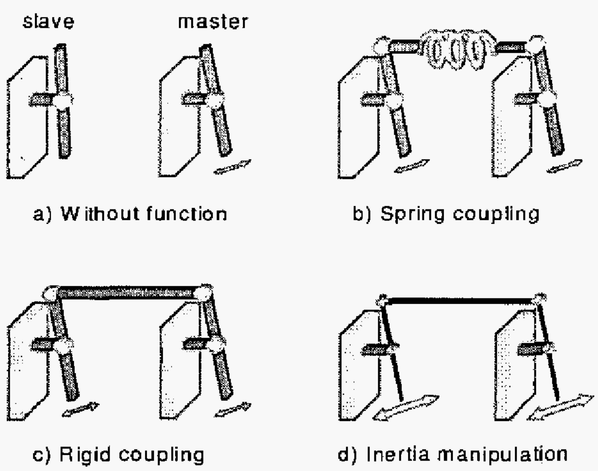

Fig. 1: Examples of functions

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

3 Coordinate transformation

In order to design the controllers based on functions, the robot information should be transformed to new coordinates based on functions. Here, the coordinates based on the information of each control object is defined as robot coordinate. On the other hand, the transformed information based on function is defined as function coordinate. In our past research, Hadamard matrix is applied for the coordinate transformation[12]. Hadamard matrix transforms variables into common and differential coordinates, that is related to the functions. Controllers are constructed in each coordinate. They are completely independent to each other. This conventional coordinate transformation method is expanded so that a position/force scaling control becomes available. Scaling matrix, a new shape of a transformation matrix for a scaling control, is introduced after the description of the conventional coordinate transformation method.

3.1 Conventional method

A conventional 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 subscript m denotes the master manipulator, subscript s denotes the slave manipulator, subscript + denotes the common coordinate and 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 to simplify the principle. The equations are applicable not only in Cartesian coordinate systems but also in rotating coordinate systems.

x_m and x_s are in the robot coordinate system. x_+ and x_- are in the function coordinate system.

Velocity and force are also able to be transformed with 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.

Force information is transformed applying the inverse of Hadamard matrix instead of normal Hadamard matrix due to the dynamics.

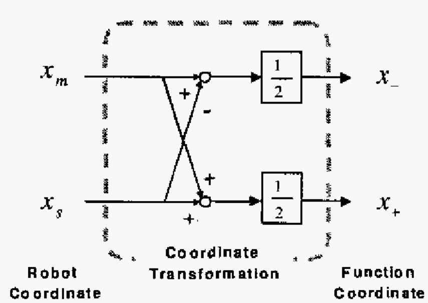

Fig. 2: Conventional coordinate transformation

Fig.2 shows the conventional coordinate transformation in a block diagram. With Hadamard matrix, the information of master and slave manipulators, are transformed to the common and differential information.

The conventional coordinate transformation is limited to the control in equal ratio. Therefore a transformation matrix with scaling factors is introduced.

3.2 Scaling matrix

A coordinate transformation expanded for a scaling control is figured out by (5).

$$\begin{aligned}\begin{bmatrix} x_+ \\ x_- \end{bmatrix} &= \frac{\beta}{\alpha+\beta}\begin{bmatrix} 1 & \alpha \\ \frac{1}{\beta} & -1 \end{bmatrix}\begin{bmatrix} x_m \\ x_s \end{bmatrix} \\ &= \frac{\beta}{\alpha+\beta}\boldsymbol{H}_s\begin{bmatrix} x_m \\ x_s \end{bmatrix} \qquad (5)\end{aligned}$$

where α denotes the scaling factor in the common coordinate and β denotes the scaling factor in the differential coordinate. $\boldsymbol{H}_s$ is the transformation matrix expanded for a scaling control. We name this scaling matrix. When $\alpha = 1$ and $\beta = 1$, this bilateral control system becomes in equal ratio and (5) becomes equivalent to (1).

Scaling matrix has the feature that its inverse is in proportion to itself. Therefore the inverse coordinate transformation is easily derived from (6).

$$\begin{bmatrix} x_m \\ x_s \end{bmatrix} = \begin{bmatrix} 1 & \alpha \\ \frac{1}{\beta} & -1 \end{bmatrix}\begin{bmatrix} x_+ \\ x_- \end{bmatrix} = \boldsymbol{H}_s\begin{bmatrix} x_+ \\ x_- \end{bmatrix} \qquad (6)$$

Velocity and force are also able to be transformed with scaling matrix as follows.

$$\begin{aligned}\begin{bmatrix} \dot{x}_+ \\ \dot{x}_- \end{bmatrix} &= \frac{\beta}{\alpha+\beta}\begin{bmatrix} 1 & \alpha \\ \frac{1}{\beta} & -1 \end{bmatrix}\begin{bmatrix} \dot{x}_m \\ \dot{x}_s \end{bmatrix} \\ &= \frac{\beta}{\alpha+\beta}\boldsymbol{H}_s\begin{bmatrix} \dot{x}_m \\ \dot{x}_s \end{bmatrix} \qquad (7)\end{aligned}$$

$$\begin{bmatrix} f_+ \\ f_- \end{bmatrix} = \begin{bmatrix} 1 & \alpha \\ \frac{1}{\beta} & -1 \end{bmatrix}\begin{bmatrix} f_m \\ f_s \end{bmatrix} = \boldsymbol{H}_s\begin{bmatrix} f_m \\ f_s \end{bmatrix} \qquad (8)$$

$$\begin{bmatrix} \tau_+ \\ \tau_- \end{bmatrix} = \begin{bmatrix} 1 & \alpha \\ \frac{1}{\beta} & -1 \end{bmatrix}\begin{bmatrix} \tau_m \\ \tau_s \end{bmatrix} = \boldsymbol{H}_s\begin{bmatrix} \tau_m \\ \tau_s \end{bmatrix} \qquad (9)$$

3.3 Dynamics

Dynamics in robot coordinates are developed to the dynamics in the function coordinates so as to show that it is reasonable to design the control system in each scaled function coordinate. Dynamic equation on master and slave coordinates under the scaling control is shown as follows.

$$M_m\ddot{x}_m + \mu_m\dot{x}_m = \tau_m + f_m \qquad (10)$$

$$M_s\ddot{x}_s + \mu_s\dot{x}_s = \tau_s + f_s \qquad (11)$$

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

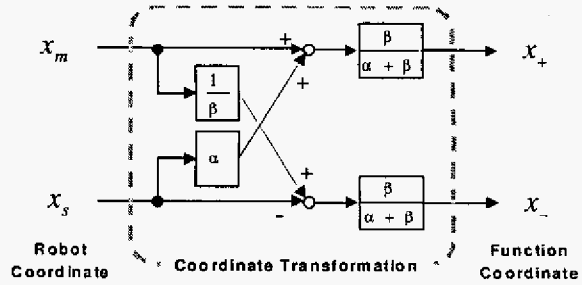

Fig. 3: Coordinate transformation from robot coordinate to function coordinate

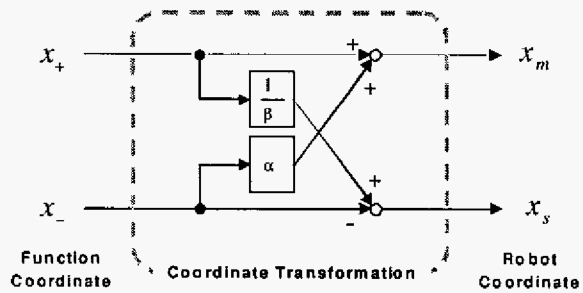

Fig. 4: Coordinate transformation from function coordinate to robot coordinate

Assume that the models of master and slave manipulators are equivalent, that is $M_m = M_s$ and $\mu_m = \mu_s$, dynamic equations in the function coordinates are developed from (10) and (11).

$$\begin{aligned} M_t\frac{\beta}{\alpha+\beta}(\ddot{x}_m + \alpha\ddot{x}_s) + \mu_t\frac{\beta}{\alpha+\beta}(\dot{x}_m + \alpha\dot{x}_s) \\ = (\tau_m + \alpha\tau_s) + (f_m + \alpha f_s) \qquad (12)\end{aligned}$$

$$\begin{aligned} M_t\frac{\beta}{\alpha+\beta}(\frac{1}{\beta}\ddot{x}_m - \ddot{x}_s) + \mu_t\frac{\beta}{\alpha+\beta}(\frac{1}{\beta}\dot{x}_m - \dot{x}_s) \\ = (\frac{1}{\beta}\tau_m - \tau_s) + (\frac{1}{\beta}f_m - f_s) \qquad (13)\end{aligned}$$

here,

$$M_t = \frac{\alpha+\beta}{\beta}M_m \qquad (14)$$

$$\mu_t = \frac{\alpha+\beta}{\beta}\mu_m. \qquad (15)$$

(16) and (17) are derived from (12) and (13).

$$M_t\ddot{x}_+ + \mu_t\dot{x}_+ = \tau_+ + f_+ \qquad (16)$$

$$M_t\ddot{x}_- + \mu_t\dot{x}_- = \tau_- + f_- \qquad (17)$$

From (16) and (17), it is shown that dynamics on common and differential coordinates could be treated same as two independent physical systems. It is able to add both inputs of a common coordinate controller and a differential coordinate controller to master or slave manipulators since the inputs are independent in the transformed coordinates. With this, controllers are available to be designed based on virtual objects with mass M_t and friction coefficient μ_t in respective function coordinates.

4 Controller composition

A composition of a function-based controller with position and force scaling is described in this section as an example.

Two functions, rigid coupling function and inertia manipulation function are introduced to achieve a transparent bilateral control. Independent controllers are designed based on the desired functions.

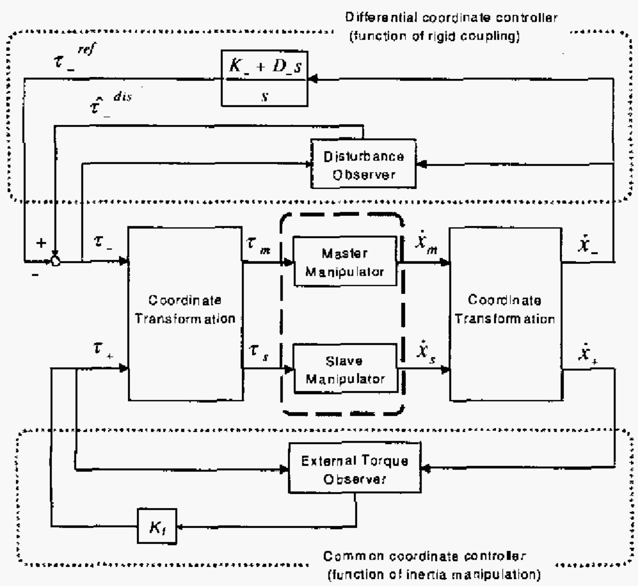

Fig. 5: Control system

The upper part of Fig.5 shows the PD controller with disturbance observer[11] in the differential coordinate. This controller realizes rigid coupling function with a robust position control system. The input torque of this control system is figured out as follows.

$$\tau_- = -(K_- + D_- s)x_- - \frac{g}{s+g}(f_- - \mu_t \dot{x}_-) \quad (18)$$

Substituting (18) to (17),

$$M_t \ddot{x}_- + D_- \dot{x}_- + K_- x_- = \frac{s}{s+g}(f_- - \mu_t \dot{x}_-). \quad (19)$$

In low frequency range, every disturbances including external force will be completely canceled. Therefore, this function of coupling will work as a rigid coupling. Since x_-, the gap of two manipulators' scaled position, will rapidly converge to zero and it would not be interfered with any other disturbances, it is reasonable to assume that $x_m = \beta x_s$ in the frequency range lower than the cutoff frequency of disturbance observer. At the same time, this function will work as a spring coupling function in the higher frequency range since disturbance observer would not sense the disturbances in a high frequency range. Although the command of position gap on differential coordinate is set to 0 for simplicity, it is also possible to give the arbitrary position gap command.

The bottom part of Fig.5 shows the controller based on the function of inertia manipulation. The sum of external force f_+ is measured and fed back in the sum coordinate. τ_+, input force in the sum coordinate, is figured out as follows.

$$\tau_+ = K_f f_+ \quad (20)$$

Substituting (20) to (16),

$$\begin{aligned} M_t \ddot{x}_+ + \mu_t \dot{x}_+ &= (1+K_f) f_+ \\ \frac{M_t}{1+K_f}\ddot{x}_+ + \frac{\mu_t}{1+K_f}\dot{x}_+ &= f_+ \\ M_v \ddot{x}_+ + \mu_v \dot{x}_+ &= f_+ \\ M_v = \frac{M_t}{1+K_f} & \\ \mu_v = \frac{\mu_t}{1+K_f}. & \end{aligned} \quad (21)$$

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

As the force feedback gain K_f becomes large, virtual mass M_v becomes small. The virtual friction coefficient μ_v also becomes small.

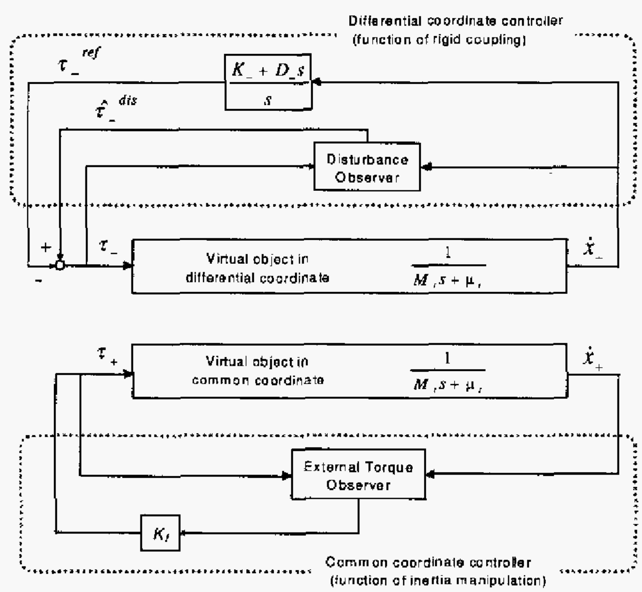

Fig. 6: Equivalent control system for virtual objects

Each controller works as if it is controlling a virtual object as shown in Fig.6. These two controllers that correspond to the rigid coupling function and the inertia manipulation function respectively. This makes the controller design explicit since the roles of the control system and the actual controllers correspond. Furthermore, individual controllers are simple because a function is a minimum component. It should be noted that the two individual controllers are designed on the function coordinates and scaling factors do not meddle in with the basic structure of controllers. Parameters of the virtual object and the relative sensor resolution vary depending on the scaling factors. This should be considered for the practical controller design.

5 Experiment

5.1 Description of experimental system

The overview of the bilateral control system is shown in Fig.7. This experimental system is composed of two equivalent 1DOF manipulators connected to a PC. The parameters of the two manipulators are shown in Table 1. The gravity term is negligible since the rotational plane of the manipulator is horizontal.

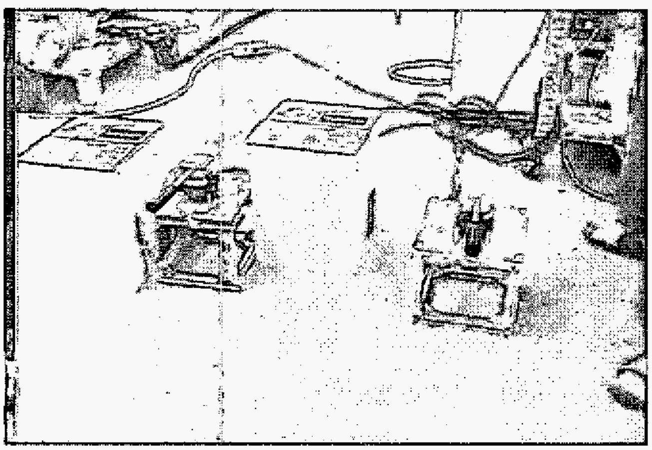

Fig. 7: Experimental system

Table 1: 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

Control parameters are shown in Table 2. These parameters are fixed in order to compare the results in different scaling factors.

Table 2: Control parameters

K_-	Position gain	2000
D_-	Velocity gain	200
K_f	Force gain	1.0
G_{dis}	DOB cutoff frequency [rad/sec]	200
t_s	Sampling time [msec]	0.1

5.2 Experimental result

Fig.8 shows the result of a position scaling experiment. Scaling factors were $\alpha = 1.0$ and $\beta = 0.333$. β shows the position scaling factor since it corresponds to coupling function in difference coordinate. At the same time, α shows the force scaling factor since it corresponds to the entire motion function in the common coordinate. The external torque value of the slave manipulator is shown upside-down in order to compare the absolute force value. The result shows that an accurate position scaling is achieved while the external force tracked each other. The gap of force responses during free motion comes from the friction and inertia torque of two manipulators. The mass of virtual object M_t became large due to the scaling factors as shown in (14). However, it is possible to reduce the virtual mass M_v if the force gain on inertia manipulation function K_f is set up larger.

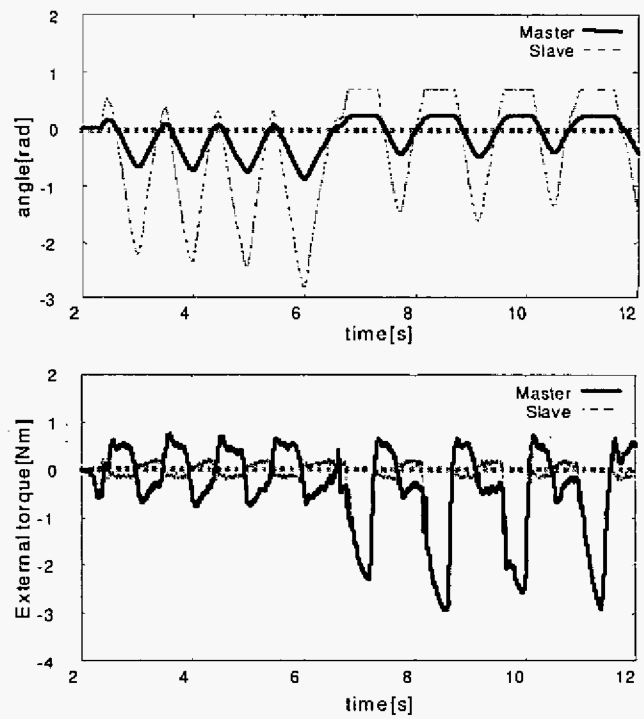

Fig. 8: Position Scaling Experiment

On the other hand, Fig.9 shows the result of a force scaling experiment. Scaling factors were $\alpha = 0.333$ and $\beta = 1.0$. An accurate force scaling is achieved while both master and slave trajectories tracked each other very well.

These results show that position/force scaling control is achieved without any interference to each other coordinate.

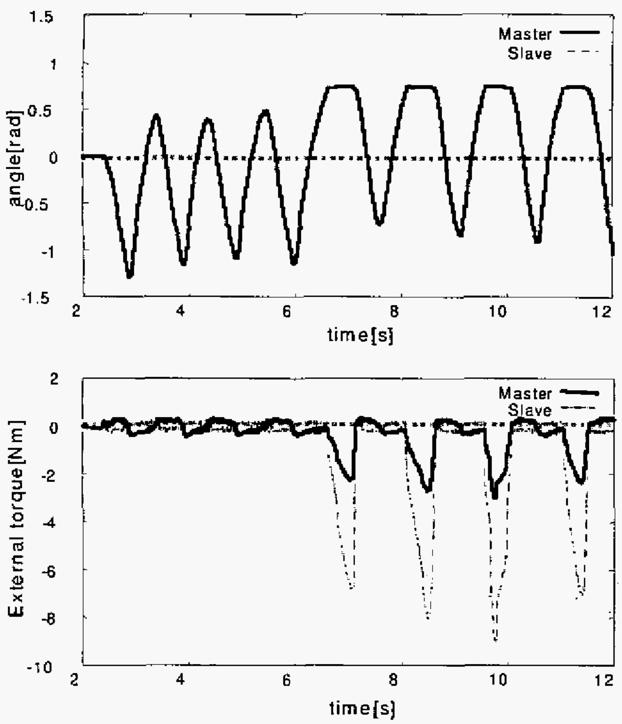

Fig. 9: Force Scaling Experiment

6 Conclusion

The concept of function leads us to an explicit and simple controller design of decentralized control systems. This paper aimed at expanding the function-based controller design method to the scaling control. Scaling matrix, a novel form of transformation matrix, was introduced in order to achieve arbitrary position/force scaling control. The position scaling control and the force scaling control are individually achieved applying scaling matrix. Dynamics of the two manipulators are transformed to the independent dynamics in function coordinates. This made possible to design each function-based controller with a simple model of a virtual object. A high transparency bilateral control was achieved with the function-based controller on scaled function coordinates. The expansion to a scaling control does not degrade the simplicity and decisiveness of the function-based controller design.

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References

[1] T. Miyazaki and S. Hagiwara, "Parallel Control Method for a Bilateral Master-Slave Manipulator", Journal of Robotics Society of Japan, Vol. 7, No. 5, pp. 446-452, 1989(in Japanese)

[2] D. A. Lawrence, "Stability and Transparency in Bilateral Teleoperation", IEEE Trans. R & A, Vol. 9, No. 5, pp. 624-637, 1993

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

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

[5] 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 Robotics Society of Japan, Vol. 8, No. 3, pp. 241-252, 1990 (in Japanese)

[6] W. Iida and K. Ohnishi, "Reproducibility and Operationality in Bilateral Teleoperation", Proc. IEEE Conf. Advanced Motion Control (AMC'04), pp. 217-222, 2004

[7] M. Morisawa and K. Ohnishi, "Motion Control Taking Environmental Information Into Account", EPE journal, Vol. 12, No. 4, pp. 37-41, 2002

[8] H. Lin and Y. Kuroe, "Decoupling Control of Robot Manipulators by Using Variable-Structure Disturbance Observer", Proc. IEEE Int. Conf. Industrial Electronics, Control and Instrumentation (IECON'95), pp. 1266-1271, 1995

[9] 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

[10] K. Kaneko, H. Takahashi, K. Tanie and K. Komoriya, "Macro-Micro Bilateral Teleoperation based on Operational Force Feedforward", Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems, pp. 1761-1769, 1998

[11] K. Ohnishi, M. Shibata and T. Murakami, "Motion Control for Advanced Mechatronics", IEEE/ASME Trans. on Mechatronics, Vol. 42, No. 2, pp. 123-130, 1995

[12] T. Tsuji, K. Natori and K. Ohnishi, "Controller Design Method of Bilateral Control Systems", Proc. EPE-PEMC2004, Riga, 2004 No. 4, pp. 123-128, 2004