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A Novel Approach to Master and Slave Control by Force Feedback Based Virtual Impedance Controller

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Abstract: A field of research which deals with tactile sensation is called haptics. Many researchers have been investigated haptics in recent years. In the past research, 4ch bilateral controller based on torque/force sensorless approach is developed so as to achieve high transparency as teleoperation systems. In actual system with geared motor, however, the high transparency leads to instability because of disturbances. In particular, the geared motor has a large joint friction which affects the torque/force sensorless control, though its cost is low. This means that the high quality of tactile sensation is not expected in case the geared motor is used in experimental system. To improve the effect of friction, linear motor is often utilized in the past research, though its cost is high. To address this issue, this paper focuses on a novel control strategy to realize low cost teleoperation systems based on the geared motor, that is, master and slave systems. To reduce the effect of joint friction, a novel approach to master and slave control by force feedback based virtual impedance controller is proposed. By using the proposed method, position and force controllers can be designed independently and it is one of remarkable features. To verify the validity of proposed method, the performance of the controller is analyzed and evaluated by using "Reproducibility" and "Operationality". Furthermore experimental validation is conducted with 1-DOF manipulator.

Keywords: Master and slave system, Force feedback, Virtual impedance control.

1. INTRODUCTION

Haptics is one of key technologies to develop a new market in robot applications. Many researchers have investigated haptics in recent years. Bilateral teleoperation with master and slave robot is one of the haptic technologies. Slave follows the master motion which is manipulated by human operator, and the operator can feel slave force through master. That is to say, touch sense of remote object must be transferred from master to slave. This technique is expected to be used in many situations such as space, surgery, nuclear reactor, tele-communication, and so on.

Various researches concerning bilateral control have been done in last several decades. Hannaford constructed the ideal relationship between master and slave system based on hybrid matrix[1] and this relationship is formulated as "Transparency"[2]. Then, acceleration control on bilateral tele-operation is achieved by disturbance observer (DOB) [3][4][5]. This enables to improve robustness and transparency of bilateral control. In addition, reaction torque observer (RTOB) has been implemented to enable force feedback without force/torque sensors[6]. In recent years, bilateral teleoperation has applied in multiple ways, for example, multi-degree-of-freedom (MDOF) bilateral system [7], bilateral teleoperation using two-wheel mobile manipulator[8], bilateral grasping control[9], and so on. Also, evaluation indices are defined in order to evaluate the controller quantitatively in bilateral control systems[10]. The target goals of bilateral teleoperation are considered as following two points. One is a reproduction of environmental impedance in master side. The other is a realization of small operational force. Corresponding to two goals, indices are defined as "Reproducibility" and "Operationality". Generally, 4ch bilateral controller is well known so as to achieve high transparency. In actual implementation, however, the high transparency leads to instability because of disturbances. In particular, the geared motor has a large joint friction which affects the torque/force sensorless control. To improve the effect of friction, linear motor is often utilized in the past approaches. They are powerful, but its cost becomes high. In this paper, teleoperation using the geared motor is taken up to achieve a realization of low cost teleoperation system. To improve the joint friction effect, a novel master and slave system is described in this paper. Force feedback based virtual impedance controller and acceleration controller are used in the proposed method. Using this approach, position and force controllers can be designed independently. This makes it possible to improve the controller performance in tele-operation systems. To verify the validity of the proposed method, the controller performance is analyzed and evaluated by using "Reproducibility" and "Operationality". Several analytical and experiments are implemented to confirm the effectiveness of the proposed method.

This paper is organized as follows. In section 2, the proposed master and slave controller is explained comparing with a general 4ch bilateral controller. In section 3, to verify the validity of the proposed method, the controller performance is analyzed by using "Reproducibility" and "Operationality". In section 4, the effectiveness of the proposed method is demonstrated by a 1-DOF manipulator. Finally, conclusions and future works are summarized in section 5.

2. MASTER/SLAVE SYSTEM BY FORCE FEEDBACK BASED VIRTUAL IMPEDANCE CONTROLLER

In this section, first, a control structure of conventional 4ch torque/force sensorless bilateral systems is simply shown. Second, the proposed method is explained. The controller consists of force feedback based virtual impedance controller of master manipulator and position controller of slave manipulator. The proposed control structure for master and slave is simple and this makes clear parameter design of the controller.

2.1 Conventional 4ch sensorless bilateral controller

4ch torque/force sensorless bilateral controller is constructed based on Disturbance observer (DOB) and Reaction torque observer (RTOB). Fig. 1. shows an overview of block diagram of conventional 4ch bilateral controller. The purpose of bilateral control is to realize a tracking control of position X in master and slave systems, and to reproduce reaction force F occurred in each system. In other words, it is to achieve a bilateral communication of position and force in master and slave systems. An ideal bilateral teleoperation system would satisfy the following conditions. Here, subscripts M and S denote master and slave, respectively.

$$X_M^{res} - X_S^{res} = 0 \tag{1}$$

$$F_M + F_S = 0 \tag{2}$$

Eqs (1) and (2) show differential mode and common mode, respectively. They illustrate ideal position tracking and realization of "law of action and reaction". Achieving both of these objectives might be conflicting simultaneously, but virtual modal decomposition enables force and position control for position tracking and force reproduction. While the force is controlled in the common mode F_+, the position is controlled in the differential mode x_- defined as follows.

$$F_+ = 0 \tag{3}$$

$$x_- = 0 \tag{4}$$

Since common mode and differential mode are orthogonal to each other, force and position are controlled simultaneously and independently. To achieve a high performance position and force control, the controller is synthesized based on the acceleration controller for both master and slave as follows.

$$\ddot{X}_M^{ref} = C_p\left(X_S^{res} - X_M^{res}\right) + C_f\left(\hat{F}_M^{ext} + \hat{F}_S^{ext}\right) \tag{5}$$

$$\ddot{X}_S^{ref} = C_p\left(X_M^{res} - X_S^{res}\right) + C_f\left(\hat{F}_S^{ext} + \hat{F}_M^{ext}\right) \tag{6}$$

Here, $C_p = K_p + K_v s$ is a position PD gain and $C_f = K_f$ is a force control gain. Eqs (5) and (6) means that position and force control is unified through acceleration dimension. Here RTOB provides an estimation of external force without torque/force sensor and brings torque/force sensorless control. Furthermore, DOB estimates disturbances and the estimated disturbance is fed back to achieve robust bilateral control. However, if the geared motor is utilized as actuator in experimental system, high touch will not be realized because it's very difficult to reduce the friction effect perfectly. Moreover the friction effect affects the controller performance significantly in torque/force sensorless teleoperation system because interactive response between position and force response is induced through the friction effect. Consequently, force and position are not controlled simultaneously and independently in conventional 4ch bilateral system using the geared motor.

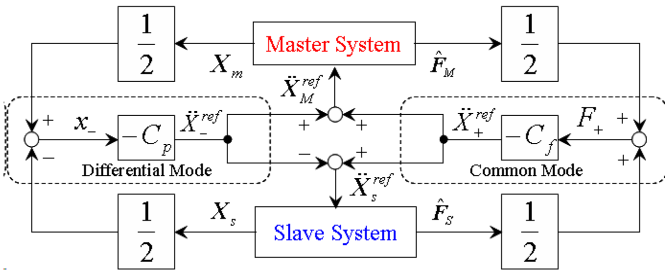

Fig. 1. Block diagram of conventional 4ch controller.

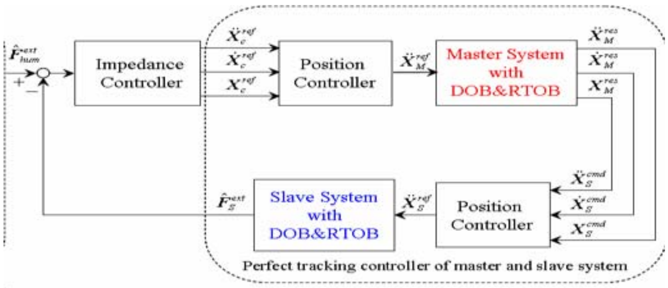

Fig. 2. Block diagram of proposed controller.

2.2 Force feedback based virtual impedance controller

To improve the motion performance in the teleoperation system based on the geared motor, this paper proposes a force feedback based virtual impedance controller and acceleration controller. Using the proposed approach, position and force controllers can be designed independently. Fig. 2. shows an overview of block diagram of the proposed controller. As shown in Fig.2., the force difference of master and slave is an input to the virtual impedance controller to generate motion commands and they are utilized to achieve a perfect tracking performance in the position controller.

In the virtual impedance controller, the desired impedance parameters M_c, D_c and K_c are defined and the difference between human input $\hat{F}_{hum}^{ext}$ and reaction force $\hat{F}_S^{ext}$ is transformed to position, velocity and acceleration command (X_c^{ref}, $\dot{X}_c^{ref}$, $\ddot{X}_c^{ref}$). A motion model of virtual impedance is given as eq. (7).

$$M_c\ddot{X}_c^{ref} + D_c\dot{X}_c^{ref} + K_c X_c^{ref} = \hat{F}_{hum}^{ext} - \hat{F}_S^{ext} \tag{7}$$

Using the generated motion commands (X_c^{ref}, $\dot{X}_c^{ref}$, $\ddot{X}_c^{ref}$), the acceleration reference is synthesized in eq. (8).

$$\ddot{X}_M^{ref} = \ddot{X}_c^{ref} + K_p\left(X_c^{ref} - X_M^{res}\right) + K_v\left(\dot{X}_c^{ref} - \dot{X}_M^{res}\right) \quad (8)$$

Here, in the DOB based controller, the acceleration control, that is, $\ddot{X}_M^{res} = \ddot{X}_M^{ref}$ is achieved from eqs. (7) and (8), and transfer function with respect to the position response is given as follows.

$$X^{res} = \frac{\frac{K_c}{M_c}}{s^2 + \frac{D_c}{M_c}s + \frac{K_c}{M_c}} \frac{1}{K_c}\left(\hat{F}_{hum}^{ext} - \hat{F}_s^{ext}\right)$$
$$= \frac{\omega_f^2}{s^2 + 2\zeta_f \omega_f s + \omega_f^2} \frac{1}{K_c}\left(\hat{F}_{hum}^{ext} - \hat{F}_s^{ext}\right) \quad (9)$$

In the proposed approach, virtual impedance gain M_c, D_c, K_c are determined so that the following performances are improved.

- Reproduction of environmental impedance in master side
- Realization of small operational force

In the impedance controller, natural angular frequency ω_f and damping constant ζ_f are defined in eqs. (10) and (11). Here ω_f is set so that the required motion response in master and slave system is satisfied and ζ_f is set to 1 for the stable response.

$$\omega_f = \sqrt{\frac{K_c}{M_c}} \quad (10)$$

$$\xi_f = \frac{D_c}{2\sqrt{M_c K_c}} \quad (11)$$

2.2 *Position controller of slave robot*

Position controller of slave manipulator is designed to track the response of master manipulator. As well as the master manipulator, acceleration reference $\ddot{X}_S^{ref}$ for the slave manipulator is given as follows.

$$\ddot{X}_S^{ref} = \ddot{X}_M^{res} + K_p\left(X_M^{res} - X_S^{res}\right) + K_v\left(\dot{X}_M^{res} - \dot{X}_S^{res}\right) \quad (12)$$

3. PERFORMANCE ANALYSIS

In this section, performance analysis with respect to the proposed controller is conducted. Here, the performance difference between proposed controller and conventional 4ch bilateral controller is analyzed by using “Reproducibility” and “Operationality”[10].

3.1 Reproducibility and Operationality

“Reproducibility” and “Operationality” are used as performance indices for “Operability”. Relationship between master and slave is defined as follows by using hybrid matrix H.

$$\begin{bmatrix} F_m \\ X_m \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \begin{bmatrix} X_s \\ -F_s \end{bmatrix} \quad (13)$$

Here, environmental impedance Z_e *is introduced as follows.*

$$F_s = Z_e X_s \quad (14)$$

From eqs. (13) and (14), the relationship between position and force is defined as follows.

$$F_m = \left(H_{11} - H_{12}Z_e\right)\left(H_{21} - H_{22}Z_e\right)^{-1} X_m = Z_t X_m \quad (15)$$

Here, Z_t *is master impedance, that is, impedance of human operator. If* Z_t *equals to environmental impedance* Z_e*, human operator can feel accurate “tactual sensation”. Then, eq. (15) can be transformed into eq. (16).*

$$F_m = \left(\frac{-H_{12}}{H_{21} - H_{22}Z_e} + \frac{H_{11}}{H_{21} - H_{22}Z_e}\right) X_m$$
$$= \left(P_r Z_e + P_o\right) X_m \quad (16)$$

Here, P_r and P_o are defined as “Reproducibility” and “Operationality” respectively. Because the reproduction of environmental impedance in master side is the most important condition in teleoperation, $P_r = 1$ should be satisfied. Additionaly, when $P_o = 0$ is realized, human operator feels real environmental impedance naturally. The ideal condition that satisfies perfect “Reproducibility” and “Operationality” is called Transparency [2]. In order to realize ideal condition, following hybrid parameters should be selected.

$$\begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \quad (17)$$

Then ideal response has been accomplished.

$$F_m = Z_e X_m \quad (18)$$

3.2 Analysis of proposed method

“Reproducibility” and “Operationality” can be easily calculated from eq. (16). In order to investigate the transition of indices, $P_r - P_o$ diagram is described [10]. The method for description is shown as follows.

I. increase position gain $K_p\left(K_p^{\min} \rightarrow K_p^{\max}\right)$

II. increase force gain $K_f\left(K_f^{\min} \rightarrow K_f^{\max}\right)$

III. decrease position gain $K_p\left(K_p^{\max} \rightarrow K_p^{\min}\right)$

IV. increase force gain $K_f\left(K_f^{\min} \rightarrow K_f^{\max}\right)$

The horizontal line represents “Reproducibility” and the vertical line represents “Operationality”. In an ideal system, “Reproducibility” and “Operationality” are 1 and 0 respectively. Assuming each parameter shown in TABLE I, $P_r - P_o$ diagram is described in Figs. 2, 3, 4 and 5. Assuming natural human motion, 2.0Hz is selected as a analytical motion frequency. Here, P_r and P_o of the proposed controller are given as follows.

$$P_r = \frac{G_L(s)\cdot C_p(s)\cdot Z_c^{-1} + G_H(s)}{\{s^2 + C_p(s) + G_H(s)\cdot Z_e\}\{G_H(s)\cdot M_n^{-1} + G_L(s)\cdot Z_c^{-1}(s)\}} \quad (19)$$

$$P_o = \frac{s^2 + C_p(s)}{\{s^2 + C_p(s) + G_H(s)\cdot Z_e\}\{G_H(s)\cdot M_n^{-1} + G_L(s)\cdot Z_c^{-1}(s)\}} \quad (20)$$

Using P_r and P_o, the performance of 4ch bilateral system has already analyzed by Iida and Ohnishi[10]. As described before, the most preferable values of P_r and P_o are 1 and 0 and then human operator can feel the real environmental impedance perfectly. From the performance analysis, when cut off frequency is 100, the proposed controller is better than 4ch controller in “Operationality”. As shown in Fig. 2 and 4, the larger position and force gain brings, the better “Reproducibility” and “Operationality”, respectively. On the other hand, as shown in Fig. 3 and Fig. 5, the lower virtual mass gain M_c brings, higher “Reproducibility” and “Operationality”. If the larger cut off frequency is selected as shown in Fig. 4 and Fig. 5, both indices becomes better. Therefore the validity of proposed method was verified through performance analysis. However, the difference between 4ch controller and proposed controller is still unclear in “Reproducibility”. In the future, this point should be discussed more.

TABLE I. Parameters for $P_r - P_o$ diagram

K_p^{min}	K_p^{max}	K_f^{min}	K_f^{max}	M_c^{max}	M_c^{min}	ω[rad/sec]
100.0	10000.0	1.0	115.0	10.0	1.2×10^{-6}	12.56 (= 2.0Hz)

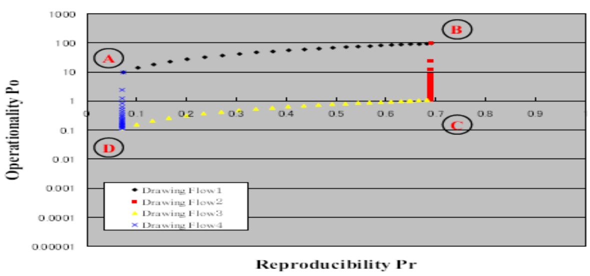

Fig.2. General 4ch architecture with *gd=100.*

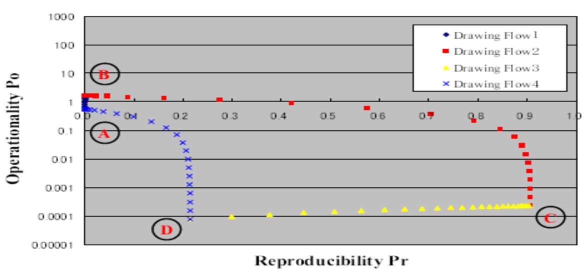

Fig.3. Proposed architecture with *gd=100.*

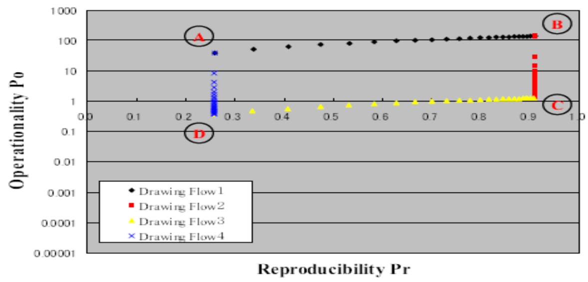

Fig.4. General 4ch architecture with gd=500.

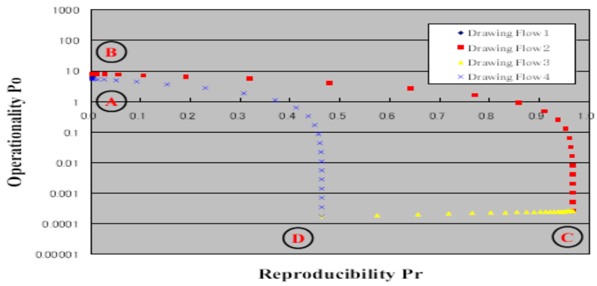

Fig.5. Proposed architecture with gd=500.

TABLE II. Experimental parameters

	Definitions	Value
K_p	Position gain	400.0
K_v	Velocity gain	40.0
K_f	Force gain	2.0
M_c	Virtual mass gain of master impedance	0.02
D_c	Virtual viscosity gain of master impedance	0.0894
K_c	Virtual spring gain of master impedance	0.03
g_d	Cut-off frequency of DOB	100.0
g_r	Cut-off frequency of RTOB	100.0
dt	Sampling time	0.001

4. EXPERIMENT

Designed controller is applied to the 1-DOF robot shown in Fig. 6. Geared motor is installed as an actuator for each master and slave. Proposed controller and 4ch bilateral controller are compared experimentally. Human operator handles quickly, and then cycles of free motion and contact motion are repeatedly conducted. Parameters in experiment are shown on TABLE II. Experimental results of torque response are shown in Fig. 7. and Fig. 8. respectively. From Fig. 7. and Fig. 8., it is found that the operational force of 4ch controller is greater than that of proposed controller in free motion. From Fig. 9 and Fig. 10, it is also found that human operator can move the robot in proposed controller faster than in 4ch controller because the operational force of proposed controller is lighter than that of 4ch controller. In 4ch controller, these are caused by the coupled effect of position and force due to some disturbances which cannot be compensated by DOB perfectly. Furthermore, the experimental system has the geared motor for each joint, so the joint friction effect affects “Operability.” On the other hand, slave follows master’s motion according to the acceleration control in proposed method, so the decoupled position and force control are well achieved and each response is controlled independently. This brings a high performance “Operability” in the proposed approach.

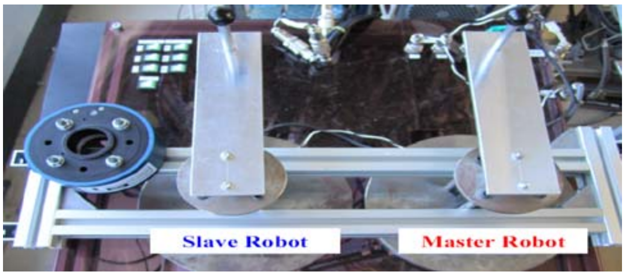

Fig.6. 1-DOF Master/Slave system with harmonic drive speed reducer.

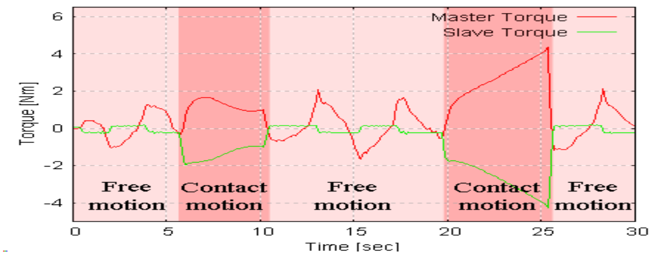

Fig. 7. Torque response of 4ch architecture

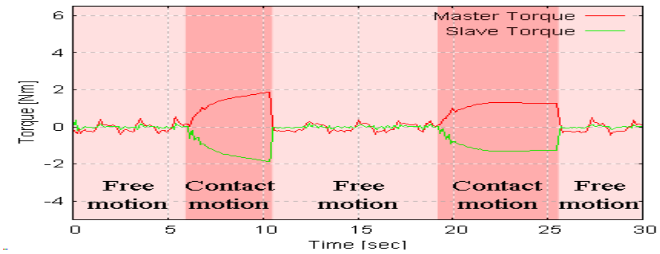

Fig. 8. Torque response of proposed architecture

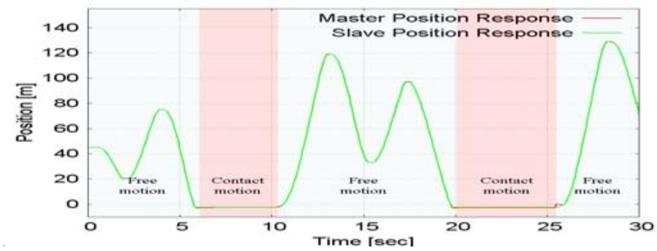

Fig. 9. Position response of 4ch architecture

Fig. 10. Position response of proposed architecture

5. CONCLUSIONS

In this paper, a novel approach to master/slave control by force feedback based virtual impedance controller is proposed. The master and slave control with virtual impedance controller is one of the remarkable points in the proposed method. By using “Reproducibility” and “Operationality”, the proposed controller is evaluated. In “Operationality”, the validity of proposed method is verified from analysis and experiment. However, in “Reproducibility”, the difference between 4ch controller and proposed controller is still unclear. In the future, this point should be discussed even more. In addition, multi-degree of freedom (MDOF) master and slave system should be verified by using the proposed method as an important future work.

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