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

Nobuhiro IWASE*, Ryosuke HORIE**
Toshiyuki MURAKAMI***

**Keio University, JAPAN (Tel: 045-566-1741; e-mail: nobuhiro@sum.sd.keio.ac.jp).*
***Keio University, JAPAN (e-mail:ryosuke@sum.sd.keio.ac.jp).*
**** Keio University, JAPAN (e-mail: mura@sd.keio.ac.jp).*

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

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 $K_f\left(K_f^{min} \rightarrow K_f^{max}\right)$

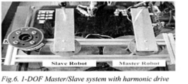

Fig.6. 1-DOF Master/Slave system with harmonic drive speed reducer.

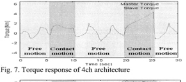

Fig. 7. Torque response of 4ch architecture

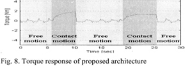

Fig. 8. Torque response of proposed architecture

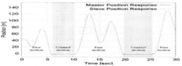

Fig. 9. Position response of 4ch architecture

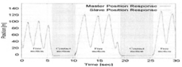

Fig. 10. Position response of proposed architecture

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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