Analysis, Modeling, and Compensation of Friction for Scaled Bilateral Control

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At present, many kinds of robots are being developed for medical care. In medical care, operations often need to be performed at the micro-scale. This study was focused on a macro-micro bilateral control system that can transmit haptic sensations of a micro-environment between master and slave systems. The macro-micro bilateral control system amplifies disturbances; therefore, analysis, modeling and compensation of the disturbances were considered.

Keywords: macro-micro bilateral control system, viscous friction, coulomb friction, scaling

1. Introduction

In the medical care, operation in micro area is necessary. Therefore, many kinds of robots are researched^{(1)–(3)}. In the almost robots, transmission of haptic sensation can not be achieved. However, in the medical robots, transmission of haptic sensation is desired. Bilateral control system is proposed as one of the master-slave teleoperation robots^{(4)–(5)}. It can transmit haptic sensation between master motor and slave motor. Many control systems based on bilateral control system are proposed. In this paper, the macro-micro bilateral control system^{(6)–(7)} which is based on bilateral control system is focused. The macro-micro bilateral control system consists of macro master motor and micro slave motor. In this system, position and force of master motor are scaled down, and those of slave motor are enlarged. The macro-micro bilateral control system can transmit haptic sensation of micro environment. Therefore, this system is useful for the sensitive operation such as minimally invasive surgery.

When master motor mass and slave motor mass are different, in order to realize the transmission of vivid force sensation from the environment, standardization matrix is proposed⁽⁸⁾. By the standardization, the mass ratio of master and slave motors is compensated. The standardization is conducted mass ratio of master and slave motor. In order to achieve high accurate control, the scaling of control gains is proposed⁽⁹⁾. In this case, the position gains of master and slave motor are different. The position gains are decided by scaling gain ratio of position and force.

In the macro-micro bilateral control system, position and force of slave motor are enlarged. Therefore, disturbances of slave motor are also enlarged. In this paper, linear motors are used as master and slave motor. Dominant disturbances of linear motors are frictions. In general, frictions are modeled as kinematic friction and static friction. In order to simplify the analysis, in this paper, only kinematic friction is considered. The kinematic friction is modeled as viscous friction

and Coulomb friction.

In this paper, effects of friction for macro-micro bilateral control system are considered based on reproducibility and operability⁽¹⁰⁾. The effects of viscous friction and Coulomb friction are separately considered. The friction coefficients are identified by using macro-micro bilateral control system. If scaling gains of position and force are different, actual environmental impedance can not be transmitted from slave motor to master motor⁽¹¹⁾. Because, in macro-micro bilateral control system, environmental impedance is dependent on scaling gains of position and force. The viscous friction is also dependent on scaling gains of position and force. On the other hand, the Coulomb friction is dependent on scaling gain of force only. By changing the scaling gains, the effects of the viscous friction and Coulomb friction can be separately enlarged. The frictions are compensated by using identified friction coefficients in the macro-micro bilateral control system.

This paper is organized as follows; Section 2 shows the macro-micro bilateral control system. In Section 3, the reproducibility and operability of macro-micro bilateral control system are explained. The effects of frictions are considered in Section 4. In Section 5, the identification of friction coefficients by macro-micro bilateral control system is explained. In Section 6, experiments are carried out. Finally, this paper is summarized in Section 7.

2. Macro-Micro Bilateral Control

In this section, macro-micro bilateral control is explained. The action force of human and the scaled reaction force satisfy the law of action and reaction. The scaled position of slave motor tracks to the position of master motor. The goals of macro-micro bilateral control are represented as follows;

$$F_m = -\beta F_s \dots\dots\dots (1)$$

$$x_m = \alpha x_s, \dots\dots\dots (2)$$

where F , x , α , β , $\odot_m$ and $\odot_s$ denote force, position, scaling gain of position, scaling gain of force, master and slave, respectively. The block diagram of macro-micro bilateral control is shown in Fig. 1, where $C_p(s)$, C_f , $\odot^{ref}$, $\odot^{ext}$, $\odot^{res}$ and

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Fig. 1. Block diagram of macro-micro bilateral control system

$\hat{\circ}$ denote position regulator, force gain, reference, external, response and estimated value, respectively. The master motor and the slave motor have DOB (Disturbance Observer) and RFOB (Reaction Force Observer)⁽¹³⁾⁽¹⁴⁾. The position regulator is PD controller as follows;

$$C_p(s) = K_p + K_v s, \dots \dots \dots (3)$$

where K_p and K_v denote position gain and velocity gain. In order to implement $K_v s$, pseudo differential is used.

3. Reproducibility and Operability

In this section, reproducibility and operability of macro-micro bilateral control system are explained. Reproducibility means reproductions accuracy of the environmental impedance. In an ideal macro-micro bilateral control system, operator can feel only environmental reaction force. However, in the actual macro-micro bilateral control system, operator feels not only environmental reaction force but also other force. The other force is operability force. Therefore, operability means the force which is in the master motor except the environmental reaction force. The relation between master and slave motor is shown with hybrid matrix as follows;

$$\begin{bmatrix} F_m \\ x_m \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \begin{bmatrix} x_s \\ -F_s \end{bmatrix} \dots \dots \dots (4)$$

The environment reaction force is shown as follows;

$$F_s = -Z_e x_s, \dots \dots \dots (5)$$

where Z_e denotes environmental impedance. The relation between master motor and environmental impedance is shown as follows;

$$F_m = \left(\frac{H_{12}}{H_{21} + H_{22}Z_e} Z_e + \frac{H_{11}}{H_{21} + H_{22}Z_e} \right) x_m \dots \dots \dots (6)$$

The reproducibility and operability of macro-micro bilateral control system are shown as follows;

$$P_r = \frac{H_{12}}{H_{21} + H_{22}Z_e} \dots \dots \dots (7)$$

Fig. 2. Block diagram of control part

$$P_o = \frac{H_{11}}{H_{21} + H_{22}Z_e} \dots \dots \dots (8)$$

where P_r and P_o denote reproducibility and operability. Fig. 2 shows control part block diagram of Fig. 1 as 4ch bilateral control system⁽¹⁵⁾, where C denotes control gain. The parameters of hybrid matrix (4) are calculated from Fig. 2 and shown as follows;

$$H_{11} = \frac{C_1 C_4 + (s^2 + C_m)(s^2 + C_s)}{C_1 C_6 + C_3(s^2 + C_m)} \dots \dots \dots (9)$$

$$H_{12} = -\frac{C_1 C_2 + C_5(s^2 + C_m)}{C_1 C_6 + C_3(s^2 + C_m)} \dots \dots \dots (10)$$

$$H_{21} = \frac{-C_3 C_4 + C_6(s^2 + C_s)}{C_1 C_6 + C_3(s^2 + C_m)} \dots \dots \dots (11)$$

$$H_{22} = \frac{C_2 C_3 - C_5 C_6}{C_1 C_6 + C_3(s^2 + C_m)} \dots \dots \dots (12)$$

The macro-micro bilateral control systems controller gains of (9) to (12) are calculated from Fig. 1 and Fig. 2. They are shown as follows;

$$-\frac{\alpha + \beta}{\alpha \beta} C_4 = \frac{\alpha + \beta}{\beta} C_m = C_p(s) \dots \dots \dots (13)$$

$$(\alpha + \beta) C_1 = \frac{\alpha + \beta}{\alpha} C_s = C_p(s) \dots \dots \dots (14)$$

$$\frac{\alpha + \beta}{\alpha \beta} C_2 = -\frac{\alpha + \beta}{\alpha} C_6 = C_f \dots \dots \dots (15)$$

$$-(\alpha + \beta) C_3 = \frac{\alpha + \beta}{\beta} C_5 = C_f \dots \dots \dots (16)$$

(13) to (16) are substituted in (9) to (12). The hybrid matrix is obtained as follows;

$$\begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} = \begin{bmatrix} -\frac{\alpha + \beta}{C_f} s^2 & \beta \\ \alpha & 0 \end{bmatrix} \dots \dots \dots (17)$$

The reproducibility and operability of macro-micro bilateral control system are calculated as follows by (7), (8) and (17),

$$P_r = \frac{H_{12}}{H_{21} + H_{22}Z_e} = \frac{\beta}{\alpha} \dots \dots \dots (18)$$

$$P_o = \frac{H_{11}}{H_{21} + H_{22}Z_e} = -\frac{\alpha + \beta}{\alpha C_f} s^2 \dots \dots \dots (19)$$

The relation between master motor and environmental impedance of macro-micro bilateral control system is shown as follows;

$$F_m = \frac{\beta}{\alpha} Z_e x_m - \frac{\alpha + \beta}{\alpha C_f} \ddot{x}_m \dots \dots \dots (20)$$

The environmental impedance is scaled depending on scaling gain α and β . In order to transmit the actual environmental impedance, the scaling gain of position and force must be equal. There is Operability in (20). Therefore, the operator feels force except for reaction force. But if the force gain is getting larger, operability becomes smaller.

4. Analysis of Friction Effect

In this section, the effects of frictions for macro-micro bilateral control system are considered. The friction of slave motor consists of viscous friction and Coulomb friction. The friction model of slave system is shown as follows;

$$F_{fric} = -D_{vis}\dot{x}_s - F_{coul} \operatorname{sgn}(\dot{x}_s), \dots \dots \dots (21)$$

where F_{fric} , D_{vis} and F_{coul} denote friction force, coefficient of viscous friction and force of Coulomb friction. The relation among slave motor, environmental impedance and friction is shown as follows;

$$\begin{aligned} F_s &= -Z_e x_s - D_{vis} \dot{x}_s - F_{coul} \operatorname{sgn}(\dot{x}_s) \\ &= -Z'_e x_s - F_{coul} \operatorname{sgn}(\dot{x}_s), \dots \dots \dots (22) \end{aligned}$$

where Z'_e denotes combination value of environmental impedance and viscous friction.

$$Z'_e = Z_e + D_{vis} s \dots \dots \dots (23)$$

The reproducibility and operability of macro-micro bilateral control system are calculated with (22). The reproducibility and operability are shown as follows;

$$F_m = \frac{\beta}{\alpha} Z'_e x_m - \frac{\alpha + \beta}{\alpha C_f} \ddot{x}_m + \beta F_{coul} \operatorname{sgn}(\dot{x}_s), \dots \dots \dots (24)$$

The environmental impedance is scaled depending on scaling gain α and β . Therefore, if $\alpha:\beta$ is 1:1 to transmit actual impedance, the environmental impedance and viscous friction are not scaled. However, the Coulomb friction is scaled dependent on force scaling gain β . Therefore, even if $\alpha:\beta$ is 1:1, the Coulomb friction is scaled.

5. Disturbance Identification

In this section, separately identification method of viscous friction and Coulomb friction is explained. When free motion is carried out, the environmental impedance is zero. Therefore, in this case, the force of master motor is shown as follows;

$$F_m = \frac{\beta}{\alpha} D_{vis} \dot{x}_m - \frac{\alpha + \beta}{\alpha C_f} \ddot{x}_m + \beta F_{coul} \operatorname{sgn}(\dot{x}_s), \dots \dots \dots (25)$$

In order to separate the effects of viscous friction and Coulomb friction, two free motions which have the same motions and different scaling gains $\alpha_1, \beta_1, \alpha_2$ and β_2 are carried out. In this case, the forces of master are shown as follows;

$$F_{m1} = \frac{\beta_1}{\alpha_1} D_{vis} \dot{x}_m - \frac{\alpha_1 + \beta_1}{\alpha_1 C_f} \ddot{x}_m + \beta_1 F_{coul} \operatorname{sgn}(\dot{x}_s) \dots \dots (26)$$

$$F_{m2} = \frac{\beta_2}{\alpha_2} D_{vis} \dot{x}_m - \frac{\alpha_2 + \beta_2}{\alpha_2 C_f} \ddot{x}_m + \beta_2 F_{coul} \operatorname{sgn}(\dot{x}_s), \dots \dots (27)$$

When $\alpha_1:\beta_1$ and $\alpha_2:\beta_2$ are 1:1, β_1 and β_2 are not the same, the difference between F_{m1} and F_{m2} is shown as follows;

Fig. 3. Experimental setup

$$F_{m1} - F_{m2} = \beta_1 F_{coul} \operatorname{sgn}(\dot{x}_s) - \beta_2 F_{coul} \operatorname{sgn}(\dot{x}_s), \dots \dots \dots (28)$$

(28) is an effect of Coulomb friction. When $\beta_1:\beta_2$ is 1:1, α_1 and α_2 are not the same, the difference between F_{m1} and F_{m2} is shown as follows;

$$\begin{aligned} F_{m1} - F_{m2} &= \left(\frac{\beta_1}{\alpha_1} - \frac{\beta_2}{\alpha_2} \right) D_{vis} \dot{x}_m \\ &+ \left(-\frac{\alpha_1 + \beta_1}{\alpha_1 C_f} + \frac{\alpha_2 + \beta_2}{\alpha_2 C_f} \right) \ddot{x}_m \dots \dots \dots (29) \end{aligned}$$

It is an effect of viscous friction and operability. When the master motor moves with constant velocity, the operability is zero. Therefore, (29) becomes the only effect of viscous friction. The independent identification of viscous friction and Coulomb friction are achieved. In this method, the viscous friction and Coulomb friction can be separated. These effects can be enlarged. Therefore, the identification can be carried out easily.

6. Experiments

In this section, the experiments of identification and compensation are carried out. Firstly, the identification of frictions is carried out. Accordingly, the compensation of friction is carried out. Experimental setup is shown in Fig. 3. It consists of master motor, slave motor and input motor. The master motor and the slave motor are satisfied with the macro-micro bilateral control system.

In the identification experiments, master motor must be moved with constant velocity. Therefore, the input motor manipulates the master motor with constant velocity.

In the friction compensation experiments, the accuracy of macro-micro bilateral control system should be obtained. Therefore, in order to implement fair manipulations of master motor, the input motor manipulates the master motor instead of human.

6.1 Identification of Coulomb Friction In this section, the identifications of Coulomb friction are carried out.

It is defined that the Coulomb friction when the velocity of motor is plus and the Coulomb friction when velocity of motor is negative are different.

The input motor moves with constant velocity 0.015 m/s. Twice free motions are carried out. The scaling gains are set to difference values as follows;

$$\alpha_1 = 10, \quad \beta_1 = 10 \dots \dots \dots (30)$$

$$\alpha_2 = 1, \quad \beta_2 = 1. \dots \dots \dots (31)$$

Results of free motions are shown in Fig. 4. The upper graph

Fig. 4. Experimental results when velocity is plus with $\alpha_1 = 10, \beta_1 = 10, \alpha_2 = 1$ and $\beta_2 = 1$

Fig. 5. Identification of Coulomb friction when velocity is plus

shows that the two results have the same velocity. The difference between F_{m1} and F_{m2} due to scaling gain is shown as follows according to (28);

$$F_{m1} - F_{m2} = 9F_{coul} \operatorname{sgn}(\dot{x}_s) \dots \dots \dots (32)$$

The value of Coulomb friction can be calculated by (33)

$$F_{coul} \operatorname{sgn}(\dot{x}_s) = \frac{F_{m1} - F_{m2}}{9} \dots \dots \dots (33)$$

The value of (33) is shown as red line in Fig. 5. The result is not constant value, because the master motor has linear slider and linear slider is inequable. Therefore, the frictions are functions of motor position. However, the constant Coulomb friction and viscous friction are wanted to compensation of frictions. Furthermore, in the result, there is static friction. Therefore, the averages of friction results are used as identified friction values. If average is used, the effect of motor position and static friction become little.

The average of (33) is -0.041 N and it is shown as green line in Fig. 5. This value is used as the Coulomb friction when velocity is plus.

Next, the Coulomb friction is identified under the condition that velocity of motor is negative. The input motor moves with constant velocity -0.015 m/s. The scaling gains are the same with (30) and (31). Results of free motions are shown

Fig. 6. Experimental results when velocity is negative with $\alpha_1 = 10, \beta_1 = 10, \alpha_2 = 1$ and $\beta_2 = 1$

Fig. 7. Identification of Coulomb friction when velocity is negative

in Fig. 6. At this time, the value of (33) is shown as red line in Fig. 7. The average of (33) is 0.011 N and it is shown as green line in Fig. 7. This value is used as the Coulomb friction when velocity is negative.

6.2 Identification of Viscous Friction In this part, the viscous friction is identified. The scaling gains of free motions are set as follows;

$$\alpha_1 = 1, \quad \beta_1 = 10 \dots \dots \dots (34)$$

$$\alpha_2 = 10, \quad \beta_2 = 10. \dots \dots \dots (35)$$

The velocity of input motor is set to 0.015 m/s. Results of free motions are shown in Fig. 8. The velocity of master motor is constant and acceleration is zero. Therefore, operability is zero. The difference between F_{m1} and F_{m2} is calculated as follows according to (29)

$$F_{m1} - F_{m2} = 9D_{vis}\dot{x}_m \dots \dots \dots (36)$$

The value of viscous friction can be calculated by (36). The velocity of master motor is 0.015 m/s

$$D_{vis} = \frac{F_{m1} - F_{m2}}{9\dot{x}_m} \dots \dots \dots (37)$$

The value of (37) is shown in Fig. 9. The average of (37) is -0.012 and it is shown as green line in Fig. 9. This value is used as viscous friction when velocity of motor is plus.

Fig. 8. Experimental results when velocity is plus with $\alpha_1 = 1, \beta_1 = 10, \alpha_2 = 10$ and $\beta_2 = 10$

Fig. 9. Identification of viscous friction when velocity is plus

Fig. 10. Experimental results when velocity is negative with $\alpha_1 = 1, \beta_1 = 10, \alpha_2 = 10$ and $\beta_2 = 10$

Next, the viscous friction is identified under the condition that velocity of motor is negative. The velocity of master motor is -0.015 m/s. The results of free motions are shown in Fig. 10. The value of calculated viscous friction is shown in Fig. 11. The average of (37) is 1.89 and it is shown as green line in Fig. 11. This value is used as viscous friction when velocity of motor is negative.

Fig. 11. Identification of viscous friction when velocity is negative

Fig. 12. Experimental results of compensation ($\alpha = 10, \beta = 10$)

6.3 Compensation of Friction In the previous parts, the coefficients of frictions are identified. In this part, the frictions are compensated according to the identified coefficients. The free motions with compensation are carried out with scaling gain $\alpha = 10, \beta = 10$ and $\alpha = 20, \beta = 20$. In order to transmit accurate environmental impedance, α and β are the same. Free motions without compensation and with compensation are carried out. In order to compare, compensation of viscous friction, compensation of Coulomb friction and compensation of viscous and Coulomb friction are carried out. The position command of input motor is set to $0.005(1 - \cos(10t))$. The results are shown in Figs. 12 and 13. $\odot_{without}$, $\odot_{vis}$, $\odot_{coul}$ and $\odot_{vis+coul}$ denote without compensation, compensation of only viscous friction, compensation of only Coulomb friction and compensation of viscous and Coulomb friction. In the ideal free motion, the force of master motor is zero. The force without compensation and the force with compensation of viscous friction are similar. The force with compensation of Coulomb friction and the force with compensation of viscous and Coulomb friction are similar, because the effect of viscous friction is not enlarged. On the other hand, the effect of Coulomb friction is enlarged. Therefore, the compensation of Coulomb friction improves the performance of macro-micro bilateral control system.

Fig. 13. Experimental results of compensation ($\alpha = 20$, $\beta = 20$)

7. Conclusion

In this paper, effects of frictions for macro–micro bilateral control system were considered with reproducibility and operability. The frictions consisted of viscous friction and Coulomb friction. The viscous friction was not enlarged if scaling gain of position and force was the same. On the other hand, Coulomb friction was enlarged according to scaling gain of force. The friction coefficient was identified by using macro–micro bilateral control system. By using macro–micro bilateral control system, the viscous friction and Coulomb friction can be separated. In order to identify the friction coefficient, the effect of friction can be enlarged by changing the scaling gain.

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