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SENSORLESS FORCE CONTROL VIA INTERNAL MODEL CONTORL BASED CONTROLLER AND ITS APPLICATIONS TO MYOELECTRIC HAND

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ABSTRACT

The scope of this paper focuses on internal model control (IMC) based controller for sensorless force control. A prototype of a myoelectric robotic hand with bio-feedback system that can be hold an object with suitable grasping force is developed in this research. The optimal force distribution of the robotic hand when grasping an object is discussed by using a new IMC based controller. The experimental results show that the proposed controller with bio-feedback is useful for detecting reflection force without additional sensors.

***Keywords* –** Internal model control, sensorless force control, disturbance estimation, myoelectric robotic hand

1. INTRODUCTION

The IMC design structure [1] is widely used for process control or mechanical system control. Although the synthetic structure is simple, it is satisfactory for the functions of disturbance rejection and trajectory tracking. By combining the IMC with a feedback, these functions become more efficient. This fact is known in the results of [2] and [3] about the disturbance estimation property. As similar studies it is known the controller based on the disturbance observers [4] for haptic motion control.

In this paper, we propose a new internal model control based controller for sensorless force control. Generally, force sensors, pressure sensors or additional sensors are required for detecting external force. However, this complicates the mechanical structure and the controller scheme for such robotic hands. To solve the problem, the estimation property of the disturbance estimation property is pointed out.

We confirm the validity of the proposed controller structure for sensorless force control through experiments. We develop a prototype of a myoelectric robotic hand (cf. [5], [6], [7]) and bio-feedback system that can hold an object with suitable grasping force. Effectiveness of the proposed controller is verified by experiments on grasping control.

2. STRUCTURE OF INTERNAL MODEL CONTROL

Consider the linear time invariant system with disturbance as follows

$$\dot{x} = Ax + B\left(u + \xi\right), \qquad y = Cx \qquad (1)$$

where $x \in R^n$ is the state vector of the control object, $u \in R^m$ is the input vector, $y \in R^p$ is the output vector. $\xi \in R^m$ is the unknown disturbance added to the input channels. In this case, reflection force on grasping control is described as unknown disturbance. Assume that the system (A, B, C) is controllable and observable, and the system has no unstable zeros. A controller of internal model control shown in Fig. 1 is considered. Here r is the set point, y is the output, ξ is the unknown disturbance, and $\hat{\xi}$ is the estimated value of the unknown disturbance. Σ_f is the transfer function of the control object with the feedback $u = F_\varepsilon x + v$, $\overline{\Sigma}_f$ is the mathematical model of the control object with feedback as follows

$$\dot{\overline{x}} = (A + BF_\varepsilon)\overline{x} + Bv, \qquad \overline{y} = C\overline{x}. \quad (2)$$

$\overline{x} \in R^n$ is the state vector of the internal model , $\overline{y} \in R^p$ is the output vector of the internal model. The feedback gain F_ε is obtained by minimizing a cost functional

$$J = \int_0^\infty \left(x^T Q x + u^T R u\right) dt \quad Q, R > 0 \quad (3)$$

as $R = I$ and $Q = \frac{1}{\varepsilon^2} I$ ($\varepsilon \to 0$). The feedback gain F_ε is described as

$$F_\varepsilon = -B^T P_\varepsilon. \qquad (4)$$

The matrix P_ε is obtained by the next Riccati equation

$$A^T P_\varepsilon + P_\varepsilon A - P_\varepsilon B B^T P_\varepsilon + \frac{1}{\varepsilon^2} C^T C = 0. \quad (5)$$

Here F_ε is the limiting feedback gain obtained by $\varepsilon \to 0$. Furthermore, $\overline{\Sigma}_f^{-1}$ is the inverse system of $\overline{\Sigma}_f$, $\overline{\Sigma}_{f\rho}^{-1}$ is the approximate inverse system of $\overline{\Sigma}_f$. $\overline{\Sigma}_{f\rho}^{-1}$ is obtained by

$$\overline{\Sigma}_{f\rho}^{-1}\overline{\Sigma}_f = diag\left\{(\rho s+1)^{-d_1}, \cdots, (\rho s+1)^{-d_m}\right\} \quad (6)$$

ρ is a small value and d_i is the integral index to obtain a proper approximate inverse system. In Fig. 1, we define these transfer functions; H_{yr} is the transfer function from the set point r to the output y, $H_{y\xi}$ is the transfer function from the unknown disturbance ξ to the output y, and $H_{\hat{\xi}\xi}$ is the transfer function from the unknown disturbance ξ to the estimated value $\hat{\xi}$. They are described as follows

$$\begin{aligned} H_{yr} &= \Sigma_f \left\{\Sigma_{f\rho}^{-1}\Sigma_f + \left(I - \Sigma_{f\rho}^{-1}\overline{\Sigma}_f\right)\right\}^{-1}\Sigma_{f\rho}^{-1} \\ H_{y\xi} &= \Sigma_f \left\{I + \Sigma_{f\rho}^{-1}\left(\Sigma_f - \overline{\Sigma}_f\right)\right\}^{-1}\left(I - \Sigma_{f\rho}^{-1}\overline{\Sigma}_f\right). \quad (7) \\ H_{\hat{\xi}\xi} &= \left\{I + \Sigma_{f\rho}^{-1}\left(\Sigma_f - \overline{\Sigma}_f\right)\right\}^{-1}\Sigma_{f\rho}^{-1}\Sigma_f \end{aligned}$$

If $\Sigma_{f\rho}^{-1}\overline{\Sigma}_f \to I$ by $\rho \to 0$, then it holds

$$\begin{aligned} &\lim_{\rho\to 0} H_{yr} \to I \\ &\lim_{\rho\to 0} H_{y\xi} \to 0 \quad (8) \\ &\lim_{\rho\to 0} H_{\hat{\xi}\xi} \to I. \end{aligned}$$

Consequently, the internal model control with state feedback obtains surpassing properties of disturbance rejection, trajectory tracking, and disturbance estimation.

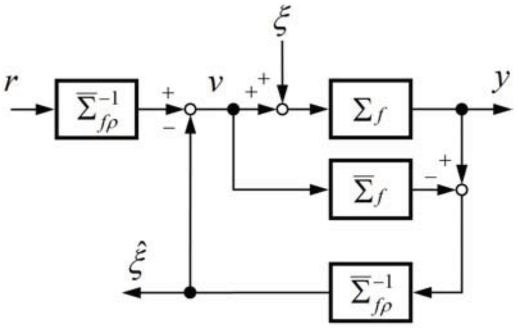

Figure 1 Internal model control structure

3. INTERNAL MODEL CONTORL STRUCTURE FOR SENSOLESS FORCE CONTROL

We point out the disturbance estimation property of the controller structure shown in Fig. 1. The controller is extended for sensorless force control. We introduce the internal model control based controller for sensorless force control in Fig. 2. α is settled as the target value of force. The estimated disturbance $\hat{\xi}$ is regulated to be the same value as α.

The system Σ_f and the model $\overline{\Sigma}_f$ of Σ_f are given as follows

$$\Sigma_f : \begin{cases} \dot{x} = (A + BF_\varepsilon)x + Bv + B\xi \\ y = Cx \end{cases}, \quad (9)$$

$$\overline{\Sigma}_f : \begin{cases} \dot{\tilde{x}} = (A + BF_\varepsilon)\tilde{x} + B(\alpha - \xi) \\ \tilde{y} = C\tilde{x} \end{cases}. \quad (10)$$

The error system $e = x - \tilde{x}$ is given as follows

$$\begin{aligned} \dot{e} &= (A + BF_\varepsilon)e + B\xi, \\ y - \tilde{y} &= Ce. \end{aligned} \quad (11)$$

The augmented system of the controller is represented as follows

$$\begin{aligned} \dot{x}_e &= A_e x_e + B_{e\xi}\xi + B_{e\alpha}\alpha \\ y &= C_{ey}x_e \\ \hat{\xi} &= C_{e\hat{\xi}}x_e \end{aligned}, \quad (12)$$

where

$$A_e = \begin{pmatrix} A_f + BD_QC & -BD_QC & -BD_QC & -BC_Q & BC_Q \\ 0 & A_f & 0 & 0 & 0 \\ 0 & -BD_QC & A_f & -BC_Q & 0 \\ 0 & B_QC & 0 & A_Q & 0 \\ B_QC & 0 & -B_QC & 0 & A_Q \end{pmatrix}, \quad (13)$$

$$B_{e\xi} = \left(B^T \quad B^T \quad 0^T \quad 0^T \quad 0^T\right)^T, \quad (14)$$

$$B_{e\alpha} = \left(0^T \quad 0^T \quad B^T \quad 0^T \quad 0^T\right)^T, \quad (15)$$

$$C_{ey} = \left(C \quad 0 \quad 0 \quad 0 \quad 0\right), \quad (16)$$

$$C_{e\hat{\xi}} = \left(0 \quad D_QC \quad 0 \quad C_Q \quad 0\right). \quad (17)$$

Moreover, the state vector of (12) system is $x_e = \left(x^T \quad e^T \quad \tilde{x}^T \quad \mu^T \quad \eta^T\right)^T$. $A_f = A + BF_\varepsilon$, and $\left(A_Q, B_Q, C_Q, D_Q\right)$ is the minimum realization of the approximate inverse system of $\overline{\Sigma}_f$. μ and η are the state vectors of the approximate inverse systems.

By using the following transformation matrix as $\overline{x}_e = Tx_e$

$$T = \begin{pmatrix} I & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & I \\ 0 & I & 0 & 0 & 0 \\ 0 & 0 & I & 0 & 0 \\ 0 & 0 & 0 & I & 0 \end{pmatrix}, \tag{18}$$

we obtain the following matrices

$$\begin{aligned} &\overline{A}_e = TA_eT^{-1}, \quad \overline{B}_{e\xi} = TB_{e\xi}, \quad \overline{B}_{e\alpha} = TB_{e\alpha} \\ &\overline{C}_{ey} = C_{ey}T^{-1}, \quad \overline{C}_{e\hat{\xi}} = C_{e\hat{\xi}}T^{-1}, \end{aligned} \tag{19}$$

where,

$$\overline{A}_e = \begin{pmatrix} A_f + BD_QC & BC_Q & -BD_QC & -BD_QC & -BC_Q \\ B_QC & A_Q & 0 & -B_QC & 0 \\ 0 & 0 & A_f & 0 & 0 \\ 0 & 0 & -BD_QC & A_f & -BC_Q \\ 0 & 0 & B_QC & 0 & A_Q \end{pmatrix} \tag{20}$$

$$\overline{B}_{e\xi} = \begin{pmatrix} B^T & 0^T & B^T & 0^T & 0^T \end{pmatrix}^T \tag{21}$$

$$\overline{C}_{e\hat{\xi}} = \begin{pmatrix} 0 & D_QC & 0 & C_Q & 0 \end{pmatrix}. \tag{22}$$

The transfer function $H_{\hat{\xi}\xi}$ from the unknown disturbance to estimated value of the unknown disturbance is described as $H_{\hat{\xi}\xi} = \overline{C}_{e\hat{\xi}}\left(sI - \overline{A}_e\right)^{-1}\overline{B}_{e\xi}$, then we obtain

$$H_{\hat{\xi}\xi} = \left\{D_Q + C_Q\left(sI - A_Q\right)^{-1}B_Q\right\}C\left(sI - A_f\right)^{-1}B. \tag{23}$$

It is clear that $H_{\hat{\xi}\xi} \to I$ by $\rho \to 0$. The next statement holds by $H_{\hat{\xi}\xi} \to I$ from Fig.2.

$$y - \Sigma_f\overline{\Sigma}_{f\rho}^{-1}y = \Sigma_f\overline{\Sigma}_{f\rho}^{-1}\overline{\Sigma}_f\left(\hat{\xi} - \alpha\right) \tag{24}$$

Therefore, we obtain

$$\hat{\xi} - \alpha \to 0 \tag{25}$$

if $\lim_{\rho \to 0}\Sigma_f\overline{\Sigma}_{f\rho}^{-1} \to I$ and $\lim_{\rho \to 0}\overline{\Sigma}_{f\rho}^{-1}\overline{\Sigma}_f \to I$. The proposed internal model control based controller shown in Fig. 2 has also the disturbance estimation property. The unknown disturbance ξ is estimated as $\hat{\xi}$ in the controller structure. Moreover, $\hat{\xi}$ is controlled by the set point α.

Next, the stability of the closed loop system is discussed. We consider the eigenvalue of the matrix $\overline{A}_e$ of the augmented system. $\overline{A}_e$ is divided into the following block matrices,

$$\overline{A}_{e11} = \begin{pmatrix} A_f + BD_QC & BC_Q \\ B_QC & A_Q \end{pmatrix}, \tag{26}$$

$$\overline{A}_{e12} = \begin{pmatrix} -BD_QC & -BD_QC & -BC_Q \\ 0 & -B_QC & 0 \end{pmatrix}, \tag{27}$$

$$\overline{A}_{e21} = \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix}, \tag{28}$$

$$\overline{A}_{e22} = \begin{pmatrix} A_f & 0 & 0 \\ -BD_QC & A_f & -BC_Q \\ B_QC & 0 & A_Q \end{pmatrix}. \tag{29}$$

The stability of the closed loop system is dependent of the eigenvalue of $\overline{A}_{e11}$ and $\overline{A}_{e22}$. A_f is stable by using the state feedback F_ε, and the realization (A_Q, B_Q, C_Q, D_Q) of the approximate inverse system $\overline{\Sigma}_{f\rho}^{-1}$ is also stable. It is clear that the eigenvalue of $\overline{A}_{e22}$ is stable. Next, the subsystem of $\overline{A}_{e11}$ is represented as the interconnected subsystem. The loop gain of this subsystem is calculated as

$$\left\| C\left(sI - A_f\right)^{-1} B\left\{D_Q + C_Q\left(sI - A_Q\right)^{-1} B_Q\right\} \right\|_\infty < 1. \tag{30}$$

Because $\overline{\Sigma}_{f\rho}^{-1}\Sigma_f$ is $diag\left\{(\rho s + 1)^{-d_1}, \cdots, (\rho s + 1)^{-d_m}\right\}$. It is clear that the $\overline{A}_{e11}$ is also stable. Therefore, the closed loop system is internally stable according to the small gain theorem.

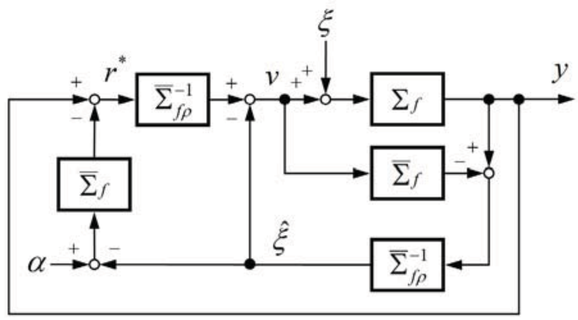

Figure 2 Internal model control structure for sensorless force control

4. APPLICATION TO SENSORLESS FORCE CONTROL ON MYOELECTRIC HAND

The proposed IMC based controller is applied to grasping force control of a myoelectric robotic hand with bio-feedback system. The prototype of the robotic hand and the model of the mechanical structure are shown in Fig. 3, Fig. 4, and Fig. 5. The robotic hand has no force sensor or pressure sensor for detecting grasping force. The prototype of the robotic hand is equipped the motor with an encoder, a microcomputer, a motor driver, and an electric circuit. The hand has three fingers driven by wire ropes. We control grasping force by using the tendon-driven mechanism [8] and one motor. The internal model control based controller shown in Fig. 2 is implemented on the microcomputer.

The mathematical model of the robotic hand is obtained as follows. Tension f of the wire is described as

$$f = 2kx + 2c\dot{x}. \quad (31)$$

By $x = r\theta$ and $\tau = fr$, the model is represented as

$$\tau = 2kr^2\theta + 2cr^2\dot{\theta}. \quad (32)$$

The physical parameters are identified $k = 0.12[N/mm]$, $r = 5[mm]$, and $c = 0.55[Ns/mm]$. The state equation of the mathematical model is

$$\Sigma : \begin{cases} \dot{\theta} = -\dfrac{k}{c}\theta + \dfrac{1}{2cr^2}\tau \\ y = \theta \end{cases} \quad (33)$$

The closed-loop system Σ_f by the feedback u is obtained as follows

$$\Sigma_f : \begin{cases} \dot{\theta} = \left(\dfrac{F_\varepsilon}{2cr^2} - \dfrac{k}{c}\right)\theta + \dfrac{1}{2cr^2}v + \dfrac{1}{2cr^2}\xi \\ y = \theta \end{cases} \quad (34)$$

where $u = F_\varepsilon\theta + v$. The model of the closed-loop $\overline{\Sigma}_f$ is described as

$$\overline{\Sigma}_f : \begin{cases} \dot{\overline{\theta}} = \left(\dfrac{F_\varepsilon}{2cr^2} - \dfrac{k}{c}\right)\overline{\theta} + \dfrac{1}{2cr^2}v \\ \overline{y} = \overline{\theta} \end{cases} \quad (35)$$

The approximate inverse system $\overline{\Sigma}_{f\rho}^{-1}$ is given by

$$\overline{\Sigma}_{f\rho}^{-1} : \begin{cases} \dot{\gamma} = -\dfrac{1}{\rho}\gamma + \omega \\ \sigma = \left(\dfrac{2kr^2 - F_\varepsilon}{\rho} - \dfrac{2cr^2}{\rho^2}\right)\gamma + \dfrac{2cr^2}{\rho^2}\omega \end{cases} \quad (36)$$

The parameter ρ for the approximate inverse system is selected as 0.015 on the experiments. The feedback gain F_ε is calculated as $F_{0.00408} = 239$. The set point α is controlled by operators as follows

$$\alpha = -50E - 100, \quad (37)$$

where E is a myoelectric signal from operators. E increases linearly by the electric circuit, if the myoelectric signal is gained. The coefficient of α is compensated by trial experiments.

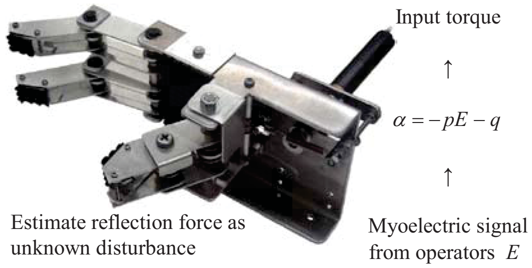

Figure 3 Tendon-driven robotic hand

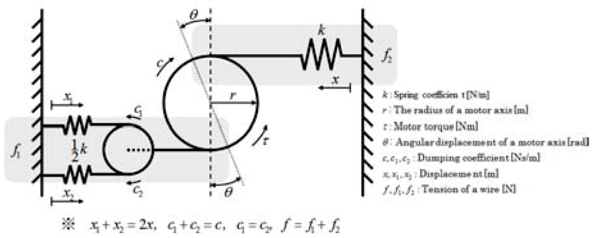

Figure 4 Model of robotic hand

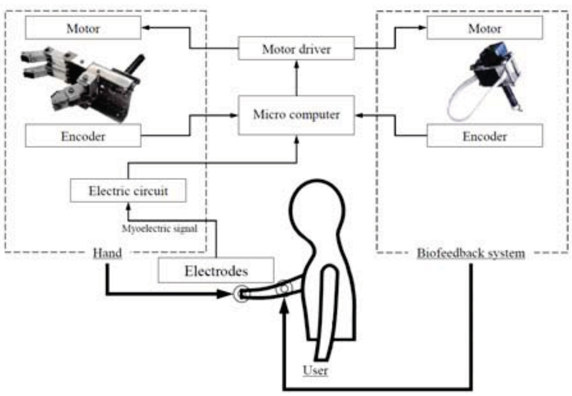

Figure 5 A prototype of myoelectric robotic hand and bio-feedback systems

5. EXPERIMENTAL RESULTS AND EVALUATIONS

Fig. 6 and Fig. 7 are experimental results on sensorless grasping control. Fig. 6 is the result of the controller shown in Fig. 2, and Fig. 7 is the result of generating the bio-feedback signal. The prototype robotic hand grasps a sponge as a grasping object by using myoelectric signals. The operator changes level of signals "gain" or "loss" for grasping the object. The myoelectric signal is concerned with the set point, and the appropriate torque to the motor is generated by the set point. If the estimated value is obtained accurately as $\varepsilon \to 0$ and $\rho \to 0$, then the proposed controller structure provides appropriate input torque.

From the result of Fig. 6, we can see that the proposed controller in Fig. 2 estimates reflection force from the sponge. It means that the proposed controller controls grasping force by estimating reflection force from the object, and generates appropriate torque to the motor for grasping the object.

From the result of Fig. 7, the proposed controller generates bio-feedback signals by estimating reflection force. The operator is able to feel reflection force from the object by using the bio-feedback system.

By using the proposed controller structures, we achieved sensorless grasping control with bio-feedback for the myoelectric robotic hand. Effectiveness of the disturbance estimation property was shown in Fig. 6 and Fig. 7. From these experiments we verified that operators can hold an object with suitable grasping force by detecting reflection force from the object.

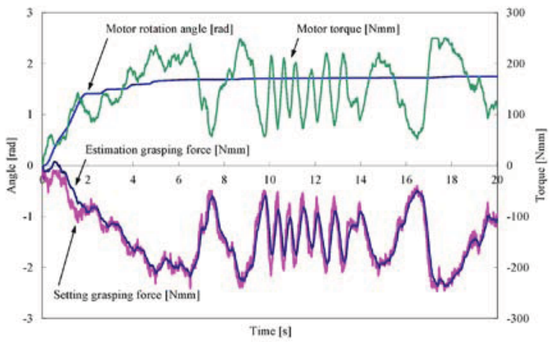

Figure 6 Experimental result on grasping control

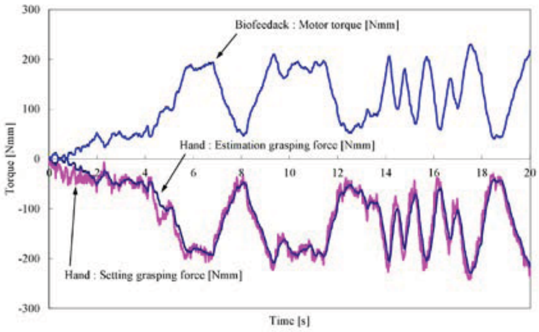

Figure 7 Experimental result on bio-feedback control

6. CONCLUSIONS

In this paper, we proposed the internal model control based controller for sensorless force control on myoelectric robotic hand. We developed the prototype of the robotic hand with bio-feedback system, and verified the proposed controller by experiments.

We confirmed effectiveness of the proposed controller on grasping control with bio-feedback. The proposed controller generated appropriate torque to the motor, and also generated bio-feedback signals for operators by estimating reflection force.

The proposed research specifically emphasizes that from theoretical and experimental findings the disturbance estimation property of the proposed controller is useful for detecting reflection force without additional sensors, e.g. force sensors or pressure sensors. The results are further step to contribute towards the development of robotic hand interacting with humans.

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