

HAPTIC FEEDBACK CONTROL FOR ROBOTIC SURGICAL FORCEPS

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Abstract: A control method for robotic surgical forceps with force sensation has been addressed in this paper. A prototype of a master-slave robotic system has been developed to evaluate the proposed control method. The mechanical structures of the master robot and the slave robot are different. Force sensors and pressure sensors are not mounted on the slave robot. These points are novel compared to another research in haptic feedback control. The internal model control has been applied to control the robotic surgical forceps in order to feedback force sensation on the slave robot. The robotic surgical forceps have been evaluated by several experiments. The experimental results show that the proposed control method is able to estimate different contact force of the forceps tips on the slave robot without force sensors, and the proposed system is also able to feedback force sensation to the operator.

Keywords: *Internal model control, force detection, haptic feedback control, robotic surgical forceps*

INTRODUCTION

Robotic surgical forceps have been developed in order to improve surgical operations. One of the most famous robotic surgical system is the da Vinci produced Intuitive Surgical Incorporated. However, the system does not have haptic feedback function on the master-slave robotic system. Operators cannot detect contact force of the forceps tips on the slave robot. The paper focuses on haptic feedback control for the robotic surgical forceps. There are several approaches to feedback force sensation to the operator.

The master-slave system with force sensors has been proposed in the paper of Hong and Jo (Hong and Jo, 2012). Although the system is able to calculate force sensation by measuring force by sensors, the mechanical structure of the system is very complicated. The other approach is to apply the disturbance observer (Nakajima et al., 2014). By using the disturbance observer, the system is able to estimate force sensation without force sensors. To estimate contact force of the tips of forceps on the slave side, the mechanical structure of the master robot and the slave robot are same components. The observer for estimating contact force is designed by a transfer function based controller.

The internal model control (IMC) has been applied to control the robotic surgical forceps in order to feedback force sensation on the slave robot (Suzuki et al., 2008a). The IMC based controller based on a state space representation has also disturbance estimation property same as the disturbance observer. We propose a control method for robotic surgical forceps with force sensation by using the IMC based controller. The new prototype is developed to evaluate the proposed control method. We try to control the master-slave system which has different structures. The mechanical structures of the master robot and the slave robot are different. This paper also shows that the proposed prototype is able to feedback different contact force of the forceps tips on the slave robot by experiments.

TELEOPERATION SYSTEM

A prototype of a master-slave robotic system shown in Fig. 1 has been developed to evaluate the proposed control method. The master robot is operated by an operator (e.g. surgeons), and the slave robot (the forceps) performs an operation in an endoscopic surgery. The master robot is shown at the top of Fig. 1, and the slave robot is shown at the bottom in Fig. 1.

The mechanical structures of the master robot and the slave robot are different. The master robot is constructed a shaft motor and a linear encoder, and the slave robot is constructed a DC motor and a rotary encoder. Force sensors and pressure sensors are not mounted on the slave robot. These points are novel compared to another research in haptic feedback control. The system configuration of the proposed system is shown in Fig. 2. The both robots are controlled by a digital signal processor.

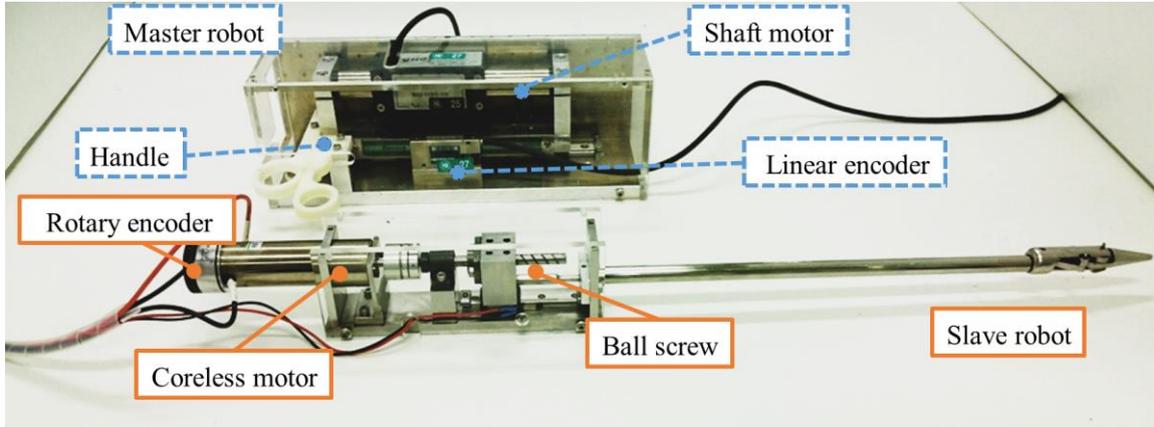


Figure 1 – Master-slave robotic system

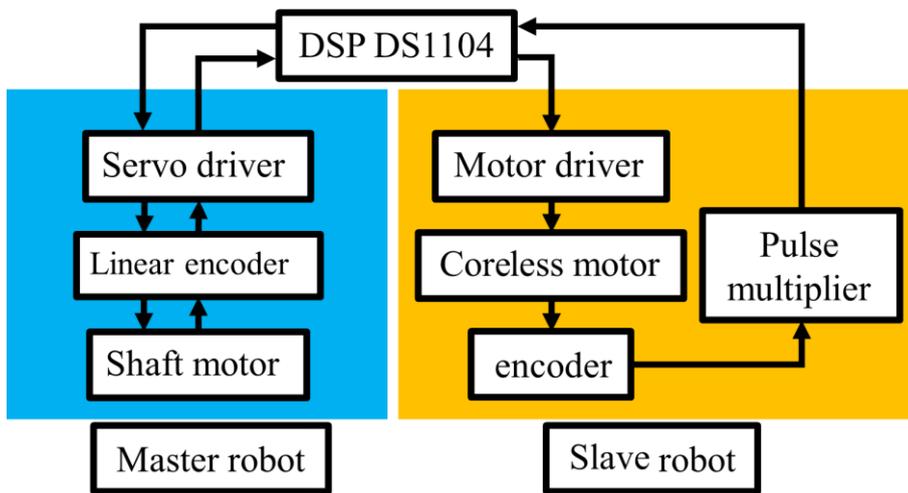


Figure 2 – System configuration of robotic system

INTERNAL MODEL CONTROL DESIGN FOR MASTER-SLAVE SYSTEM

The IMC scheme is shown in Fig. 3. This controller scheme contains the following sub-systems. Σ_{sf} is a control object with feedback (a stable system), $\bar{\Sigma}_{sf}$ is a mathematical model of the control object, and $\bar{\Sigma}_{sf\rho}^{-1}$ is an approximate inverse system of $\bar{\Sigma}_{sf}$. Although the structure is simple, it is satisfactory for the functions of disturbance rejection and trajectory tracking. The controller scheme has also disturbance estimation property (Suzuki et al., 2007).

We consider the following single input single output (SISO) system.

$$\begin{cases} \dot{x} = Ax + b(u + \xi) \\ y = cx \end{cases} \quad (1)$$

where x is the state, u is the input, ξ is the disturbance, and y is the output. The feedback gain $f_\varepsilon = -b^T P_\varepsilon$ is obtained by minimizing a cost functional

$$\tilde{J} = \int_0^\infty (x^T Q x + u^T R u) dt, \quad (2)$$

as $R = I$ and $Q = \frac{1}{\varepsilon^2} I$. P_ε is obtained by the next Riccati equation as $\varepsilon \rightarrow 0$

$$A^T P_\varepsilon + P_\varepsilon A - P_\varepsilon b b^T P_\varepsilon + \frac{1}{\varepsilon^2} c^T c = 0. \quad (3)$$

The approximate inverse system $\bar{\Sigma}_{sf\rho}^{-1}$ is obtained by the following statement.

$$\bar{\Sigma}_{sf\rho}^{-1}(s) \bar{\Sigma}_{sf}(s) = (\rho s + 1)^{-d} \quad (4)$$

where $\rho \ll 1$ and d is a minimal integral index. And then focusing attention on the transfer function Σ_{yr} and $\Sigma_{\xi\xi}$, those transfer functions are satisfied the following statements by choosing $\rho \rightarrow 0$.

$$\Sigma_{yr}(s) = \bar{\Sigma}_{sf} \bar{\Sigma}_{sf\rho}^{-1} \rightarrow 1 \quad (5)$$

$$\Sigma_{\xi\xi}(s) = \bar{\Sigma}_{sf\rho}^{-1} \bar{\Sigma}_{sf} \rightarrow 1 \quad (6)$$

These two statements mean that the IMC scheme has a trajectory tracking property and a disturbance estimation property. The disturbance ξ added to input channel is able to estimate as $\hat{\xi}$ on the controller scheme of Fig. 3.

Next, we consider to apply the IMC scheme for the master-slave robotic system. The IMC scheme for master-slave system is shown in Fig. 4. In this case, the slave robot is the control object. The estimated disturbance $\hat{\xi}$ is fed back to the operator. The operator will be able to feel estimated contact force, and then the operator is able to give appropriate input value to the master robot.

The master system Σ_m in Fig. 4 is described as follows

$$\Sigma_m \begin{cases} \dot{x}_m = A_m x_m + b_m (u_m + \hat{\xi}) \\ y = c_m x_m \end{cases}. \quad (7)$$

This master system is stable. The control input for the block diagram in Fig. 4 is described as $u = \bar{\Sigma}_{sf\rho}^{-1}(s) \Sigma_m(s) (u_m + \hat{\xi}) - \hat{\xi}$. The estimate of disturbance ξ is able to detect as $\hat{\xi}$ in Fig. 4. We construct the master-slave system without force sensors by applying the disturbance estimation property of the IMC scheme.

The augmented system is obtained as follows

$$\begin{cases} \dot{x}_e^* = A_e^* x_e^* + B_{e1}^* u_m + B_{e2}^* \xi \\ y_e^* = C_e^* x_e^* \end{cases}$$

$$A_e^* = \begin{pmatrix} A + bf_\varepsilon & -bd^+c & -bc^+ & bd^+c_m & bc^+ \\ 0 & A + bf_\varepsilon & 0 & 0 & 0 \\ 0 & b^+c & A^+ & 0 & 0 \\ 0 & b_m d^+c & b_m c^+ & A_m & 0 \\ 0 & 0 & 0 & b^+c_m & A^+ \end{pmatrix}, B_{e1}^* = \begin{pmatrix} 0 \\ 0 \\ 0 \\ b_m \\ 0 \end{pmatrix}, B_{e2}^* = \begin{pmatrix} b \\ b \\ 0 \\ 0 \\ 0 \end{pmatrix}, C_e^* = \begin{pmatrix} 0 & c \\ 0 & 0 \\ 0 & 0 \\ c_m & 0 \\ 0 & 0 \end{pmatrix}^T, \quad (8)$$

$$x_e^* = \begin{pmatrix} x \\ e \\ \eta \\ x_m \\ x^+ \end{pmatrix}, y_e^* = \begin{pmatrix} y \\ y_m \end{pmatrix}$$

The minimum realization of $\bar{\Sigma}_{sf\rho}^{-1}$ is represented as (A^+, b^+, c^+, d^+) , and $e = x - x_m$, x^+ and η are internal variables.

The transfer function from u_m to y is obtained as follows

$$H_{sm}(s) = c(sI - A - bf_\varepsilon)^{-1} b \left\{ d^+ + c^+ (sI - A^+)^{-1} b^+ \right\} c_m (sI - A_m)^{-1} b_m.$$

Therefore, the output of the slave robot is realized as $\varepsilon \rightarrow 0$ and $\rho \rightarrow 0$

$$Y(s) = c_m (sI - A_m)^{-1} b_m \{ U_m(s) + \Xi(s) \}. \quad (9)$$

The output of the slave robot is depended on the input value through the master robot controlled by the operator. If ξ is able to estimate precisely, then the operator feels contact force on the slave robot. And the operator provides appropriate input to the master robot. The operator is able to control the input value after detecting contact force on the forceps tips.

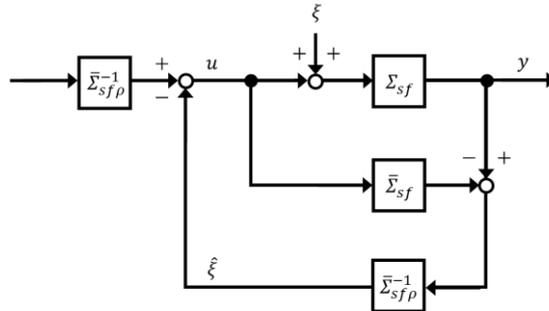


Figure 3 – Internal model control design

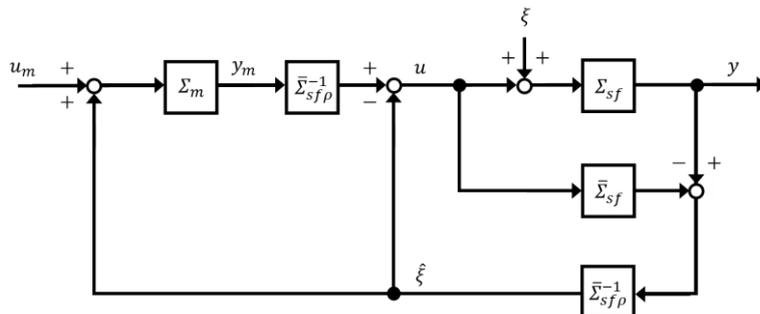


Figure 4 – Internal model control design for master-slave robotic system

EXPERIMENTS AND EVALUATION

The mathematical model of the slave robot is obtained as follows,

$$J\ddot{\theta}_s + \tilde{c}\dot{\theta}_s = T_s \quad (10)$$

where parameters are described in Fig. 5. The state space model is represented as follows,

$$\bar{\Sigma}_s \begin{cases} \dot{x} = \begin{pmatrix} 0 & 1 \\ 0 & -\tilde{c}/J \end{pmatrix} x + \begin{pmatrix} 0 \\ 1/J \end{pmatrix} \tilde{u} \\ y = (1 \ 0)x \end{cases} \quad (11)$$

Here, the input \tilde{u} is motor torque T_s , the state x is $(\theta_s \ \dot{\theta}_s)^T$ and y is the output. Then, the slave system compensated with feedback $\tilde{u} = (f_1 \ f_2)x + v$ is represented as follows

$$\bar{\Sigma}_{sf} \begin{cases} \dot{x} = \begin{pmatrix} 0 & 1 \\ f_1/J & -f_2/J - \tilde{c}/J \end{pmatrix} x + \begin{pmatrix} 0 \\ 1/J \end{pmatrix} v \\ y = (1 \ 0)x \end{cases} \quad (12)$$

The approximate inverse system is calculated as follows

$$\bar{\Sigma}_{sf\rho}^{-1} \begin{cases} \dot{z} = \begin{pmatrix} 0 & 1 \\ -\frac{1}{\rho^2} & -\frac{2}{\rho} \end{pmatrix} z + \begin{pmatrix} 0 \\ 1 \end{pmatrix} \gamma \\ w = \begin{pmatrix} -\left(\frac{f_1}{\rho^2} + \frac{J}{\rho^4}\right) & \left(\frac{\tilde{c} - f_2}{\rho^2} - \frac{2J}{\rho^3}\right) \end{pmatrix} z + \frac{J}{\rho^3} \gamma \end{cases} \quad (13)$$

z is the state, γ is the input, and w is the output of the approximate inverse system. The surgical forceps controller in Fig. 4 is designed by those sub-systems.

The proposed master-slave system is evaluated by several experiments. The design parameters are selected in Table 1. The experimental results for evaluating estimation property and for tracking property are shown in Fig. 6 and in Fig. 7.

The experimental result of tracking control is shown in Fig. 6. The ratio of range of motion of the master robot and the slave robot is 10:1. The data of the displacement of the forceps is plotted ten times as large as the real data. The result in Fig. 6 shows that the slave robot follows well the movement of the master robot.

Fig. 7 shows the experimental results of contact force estimation. The operator manipulates the master robot for picking three types of targets (resin, gel, drinking straw). The solidity of the targets is measured by a digital force gauge (DFG, a digital durometer). The solidity of resin is 6.49[N], the solidity of gel is 3.80[N], and the solidity of drinking straw is 2.35[N] respectively. From the experimental results of picking targets, we can see that the proposed control method is able to estimate different contact force of the forceps tips on the slave side without force sensors. Moreover, the proposed system is also able to feedback force sensation to the operator.

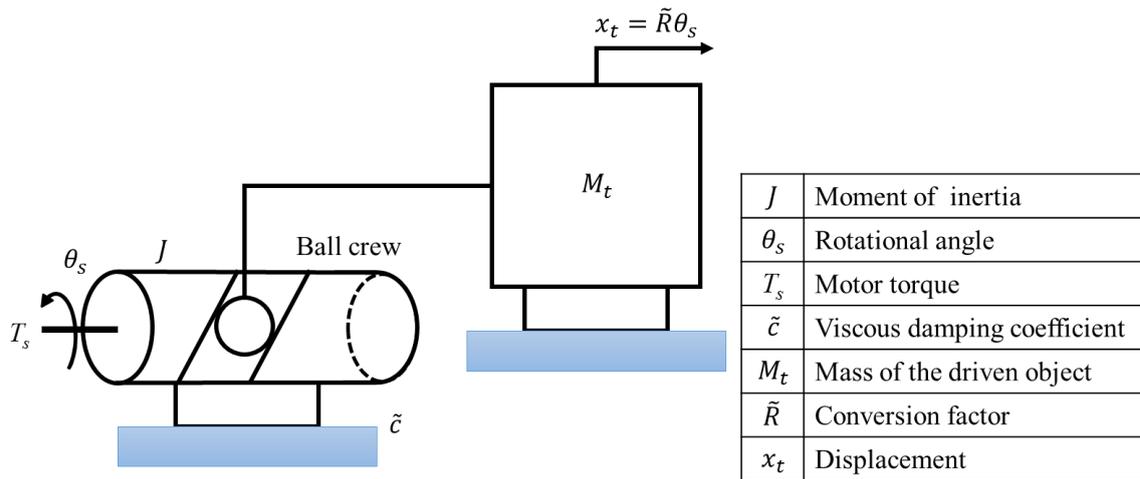


Figure 5 – Model of slave robot

Table 1 – Design parameters

Experimental parameter	Value
Moment of inertia	1.003×10^{-3}
Viscous damping coefficient	1.000×10^{-2}
ρ	7.330×10^{-3}
ε	8.124×10^{-1}

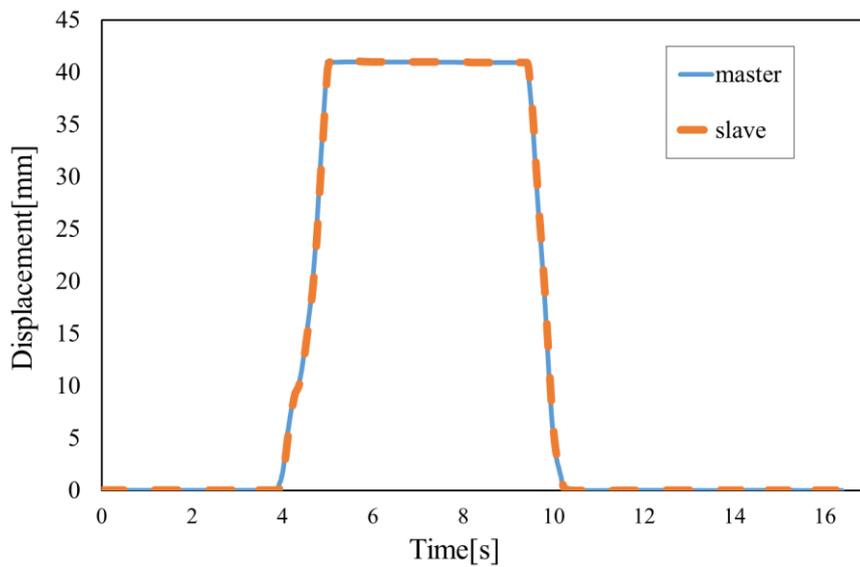


Figure 6 – Tracking property

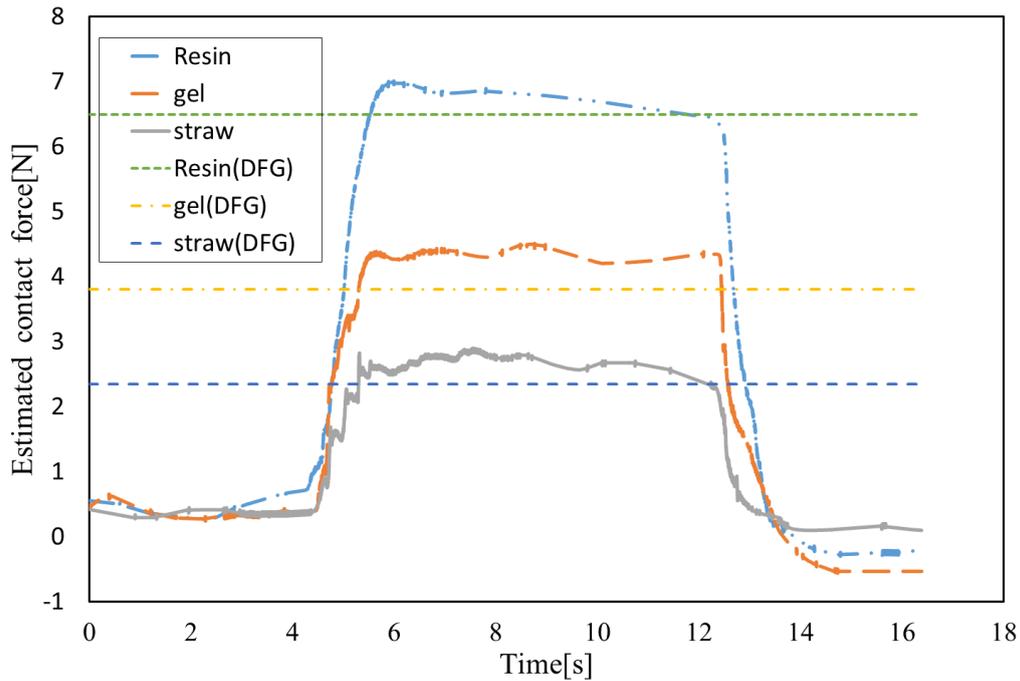


Figure 7 – Estimation of contact force

CONCLUSION

This paper has proposed the control method for haptic feedback for the master-slave robotic surgical forceps by using the IMC based controller scheme. Effectiveness of the control method for haptic feedback has been verified by experiments on the master-slave robotic system. As a future work, we will apply the observer-based stabilizing controller (Suzuki et al., 2008b) to control the proposed prototype.

REFERENCES

- Hong, M. B., and Jo, Y. H.: Design and Evaluation of 2-DOF Compliant Forceps with Force-Sensing Capability for Minimally Invasive Robot Surgery: *IEEE Transactions on Robotics*, vol. 28, no. 4, pp. 932-941, Aug. 2012.
- Nakajima Y., Nozaki, T., and Ohnishi, K.: Heartbeat Synchronization with Haptic Feedback for Telesurgical Robot: *IEEE Transactions on Industrial Electronics*, vol. 61, no. 7, pp. 3753-3764, July 2014.
- Suzuki, R., Fujiki, N., Ikeda, M., Kobayashi, N., Hofer, E. P.: Force Detection by Using Internal Model Control Scheme and Its Applications to Teleoperation with Time Delay. In: *Advances in Mechanics: Dynamics and Control*. (Ed. Felix L. Chernousko, Georgy V. Kostin, Vasily V. Saurin) Moscow: Nauka, pp. 289-295, 2008.
- Suzuki, R., Fujiki, N., Sugawara, A., Kobayashi, N. and Ito, K.: State and Disturbance Estimation Based on Internal Model Control Structure and Its Application to Sensorless Grasping Control, *Proceedings of the 33rd Annual Conference of the IEEE Industrial Electronics Society (IECON)*, Taipei, Taiwan, pp. 2846-2851, 2007.
- Suzuki, R., Ito Y., Kobayashi, N.: Disturbance Estimation by Observer-based Stabilizing Controller with Simplified Design and Its Application to Teleoperation, *Proc. of 2008 IEEE International Conference on Multisensor Fusion and Integration for Intelligent systems*, pp. 510-515, 2008.

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