CONTROL OF A 6-DOF HAPTIC FEEDBACK DEVICE FOR ROBOTIC TELEOPERATION

ĐIỀU KHIỂN THIẾT BỊ PHẢN HỒI XÚC GIÁC 6 BẬC TỰ DO VÀ ỨNG DỤNG CHO VIỆC HOẠT ĐỘNG TỪ XA CỦA RÔ BỐT

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ABSTRACT

A new force control model of a haptic feedback device for the robotic teleoperation is analyzed. Forces applied to the haptic device through human hand movements are modeled as disturbances to the force control system. A detailed analysis for modeling haptic device and human hand is provided. A self-tuning Fuzzy PID control scheme is proposed to improve system transparency by achieving good force tracking performance. This controller is developed for tuning PID gains based on the environment-slave contact force and the human-haptic device contact force in realtime. Teleoperation of a 6-DOF slave serial robot using a 6-DOF master haptic device is demonstrated. Experiment results provide good force tracking comparison in the haptic feedback teleoperation system.

Key words: Haptic feedback device; robotic teleoperation; self-tuning fuzzy pid; force control; haptic device modeling

TÓM TẮT

Bài báo này trình bày một mô hình toán học mới cho thiết bị phản hồi xúc giác. Lực của tay người khi cầm nắm thiết bị phản hồi xúc giác sẽ được mô hình hóa như nhiễu ngoài tác động vào hệ thống điều khiển. Để làm giảm ảnh hưởng của nhiễu ngoài thì bộ điều khiển mờ PID tự chỉnh được sử dụng để chỉnh định các tham số PID truyền thống dựa trên thực nghiệm với cảm biến lực. Trong một hệ thống hoàn chỉnh thì thiết bị phản hồi xúc giác đóng vai trò là thiết bị chủ và một một rô bốt hoạt động ở môi trường làm việc thực tế sẽ là thiết bị tớ. Người sử dụng cầm nắm và di chuyển thiết bị phản hồi xúc giác để tạo ra chuyển động cho rô bốt. Với bộ điều khiển mờ PID tự chỉnh, lực cảm giác trên tay người khi cầm nắm thiết bị xúc giác sẽ bám tốt hơn lực mong muốn truyền về từ rô bốt. Kết quả thực nghiệm đã chứng minh rằng lực bám được cải thiện đáng kể so với điều khiển PID truyền thống.

Từ khóa: Điều khiển robot; mô hình hóa robot; điều khiển mờ PID tự chỉnh; điều khiển lực, thiết bị phản hồi xúc giác

1. Introduction

The Haptic feedback device has become an active research area since the computing power of the processors increased rapidly. The haptic feedback teleoperation is especially useful for handling remote objects in hostile environments or in a special environment such as in a minimal invasive surgery. The teleoperation of slave robots using haptic devices should satisfy two main objectives: position control of the slave robot and accurate force sensing from the environment. For the position control the haptic device should provide the real-time trajectory commands for the slave robot to track. The user should feel actual forces from the environment not those of the structure of the haptic device. Impedance force control and admittance force control are two force control techniques used for the teleoperation of haptic devices [1]. The closed loop impedance control may improve the force performances [2-3].

Human hand and arm interact with a haptic device may affect the force control performance. Human hand impedance can be modeled as a mass-spring-damper system [6]. The human hand can be defined as an admittance model where the force input generates the motion output [7-8]. This model is constructed with one mass, two springs and two dampers. Human hand and arm should be properly modeled and included in the haptic force control system. Thus a new force control model of a haptic feedback device is analyzed in this paper.

A PID controller was selected for the teleoperation of haptic device [3]. Those results indicated that the force tracking error performances can be improved if tuning PID parameters. Although self-tuning fuzzy PID controllers show good performances in [11]-[12], their application in the haptic teleoperation system is limited. Therefore a self-tuning fuzzy PID force controller is proposed to improve force performances and reduce effects of human hand disturbances.

2. Modeling of haptic feedback device

A haptic teleoperation system in Figure 1 consists of a master device (a 6-DOF parallel haptic device), a slave robot (a 6-DOF serial robot) and an environment with a mass-spring-damper [3]. The 6-DOF haptic feedback device utilizes two 3-DOF parallel structures similar to the 3-DOF Delta structure. These two 3-DOF parallel structures are divided into the upper structure and the lower structure. The end effectors of the upper and lower structures are connected to a steering handle via universal joints. The contact forces F_c exerted by the user can be measured with two 3-DOF force sensors attached on the end effectors of the haptic device. The external contact forces F_d from the environment are also measured by a 6-DOF force sensor attached on the end effector of the slave robot.

In the haptic teleoperation system, users can hold the steering handle of haptic device to move the slave serial robot. The contacting force, F_d on the slave robot measured with 6 DOF force sensor is the desired value to the force control system while the measured force F_c on the haptic device is the feedback value.

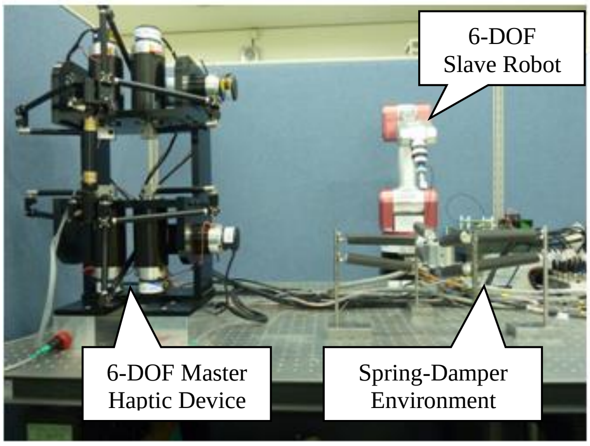

***Figure 1**. A haptic feedback teleoperation system*

A dynamic equation of 6-DOF haptic feedback device can be expressed in the Cartesian space as;

$$M\left(x_h\right)\ddot{x}_h + V\left(x_h, \dot{x}_h\right) + G\left(x_h\right) = J_h^T\tau - F_c \quad (1)$$

where τ is a motor torque vector, J_h is Jacobian and $J_h^T\tau$ is forces generated by motor torques. $M\left(x_h\right)$, $V\left(x_h, \dot{x}_h\right)$, and $G\left(x_h\right)$ are inertia matrix, coupling velocity matrix, and gravity force of the haptic device respectively. $x_h = \left[x\ y\ z\ \alpha\ \beta\ \gamma\right]^T$ is position vector of the steering handle. The contact force F_c between the steering handle and the user hand is defined as;

$$F_c = B\left(\dot{x}_h - \dot{x}_u\right) + K\left(x_h - x_u\right) \quad (2)$$

where B, K, $F_c = \left[F_x\ F_y\ F_z\ M_x\ M_y\ M_z\right]^T$, and $x_u = \left[\hat{x}\ \hat{y}\ \hat{z}\ \hat{\alpha}\ \hat{\beta}\ \hat{\gamma}\right]^T$ are damping matrix, stiffness matrix, contact force vector, and position vector of the user hand respectively. The gravity force $\tilde{G}\left(x_h\right)$ can be estimated using a classical dynamic analysis and compensated with feed-forward control action. The dynamic equation is reorganized as;

$$M\left(x_h\right)\ddot{x}_h + V\left(x_h, \dot{x}_h\right) + G\left(x_h\right) = J_h^T\tau - F_c + \tilde{G}\left(x_h\right) \quad (3)$$

If the estimated gravity force is perfect, the dynamic equation can be shortened as;

$$M\left(x_h\right)\ddot{x}_h + V\left(x_h, \dot{x}_h\right) = J_h^T \tau - F_c \tag{4}$$

The user hand keeps the steering handle of the haptic device and generates the trajectories, x_u and x_h. The user hand can be modeled as a simple 1-DOF mass-spring-damper model [7]. Relationship between the estimated hand trajectory x_u and haptic device trajectory x_h, is expressed as;

$$\hat{H} = \frac{x_u}{x_h} = \frac{\left(bs + k\right)}{m_u s^2 + \left(b + b_1\right)s + \left(k + k_1\right)} \tag{5}$$

The user hand has nonlinear stiffness and damping since its stiffness and damping change by the grab condition and posture of the arm. The dynamics of the 6-DOF haptic device including the user hand can be decoupled under slow movements and represented as a 1-DOF dynamic model.

A simple 1-DOF teleoperation system is shown in Figure 2. The trajectory x_h of haptic device can be determined by encoders while the hand trajectory x_u is difficult to measure accurately. The purpose of haptic device is to generate motions for the robot device and provide feeling forces on the user hand. Therefore design of force controller is the main task for the haptic device while design of position controller is the main task for the robot device. The trajectory of the haptic device is used as a desired trajectory for the robot device. This trajectory is controlled by a position controller K_r so the real trajectory x_r may track that of the haptic device. The user can control the robot device visually so that its tool may contact with an environment defined as a spring k_e and a damper b_e. The contacting force F_d between the environment and robot device can be measured by a force sensor. Because of robot device dynamics and contact force F_d, the real position of robot device may differ from that of the haptic device.

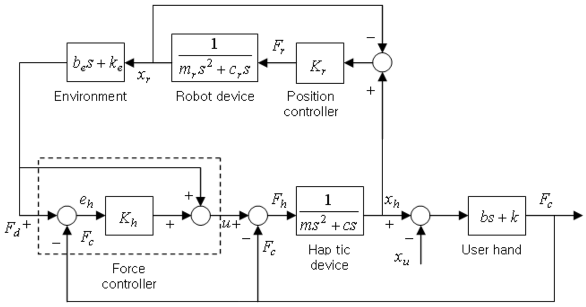

***Figure 2**. A 1-DOF teleoperation control system*

The contacting force F_d is used as a desired force for the haptic device. The user hand may feel the force F_c as the desired force F_d even though the disturbance force from user hand are existed in the system. The error between the desired force F_d and feedback force F_c is controlled by a force controller K_h to supply torques for motors of the haptic device.

The closed loop relationship between F_d and F_c in 1-DOF force model is described as;

$$F_c = \frac{\left(bs + k\right)\left(K_h + 1\right)}{ms^2 + cs + \left(bs + k\right)\left(K_h + 1\right)} F_d - \frac{\left(bs + k\right)\left(ms^2 + cs\right)}{ms^2 + cs + \left(bs + k\right)\left(K_h + 1\right)} x_u \tag{6}$$

Equation (6) implies that the contact force F_c is induced by two inputs of the user hand trajectory x_u and the desired force F_d. Equation (6) can be reformulated as;

$$F_c = \frac{\left(bs + k\right)\left(K_h + 1\right)}{ms^2 + cs + \left(bs + k\right)\left(K_h + 1\right)} \left(F_d - F_u\right) \tag{7}$$

where $F_u = \dfrac{\left(ms^2 + cs\right)x_u}{K_h + 1}$ is the dynamic force caused by the user hand movements. The force F_u driven by x_u works as a disturbance and can be reduced by increasing the control gains of K_h. The user hand trajectory can be estimated from $x_u = \hat{H}x_h$, though the dynamic properties in $\hat{H}$ change by grab condition and arm posture and are difficult to obtain in real time operation. Assume that x_e is small enough compared to x_u, the force F_u can be expressed as;

$$F_u = \frac{(ms^2+cs)x_u}{K_h+1} = \frac{(ms^2+cs)\hat{H}x_h}{K_h+1} \approx \frac{(ms^2+cs)x_h}{K_h+1} \quad (8)$$

Equation (8) implies that the haptic device dynamic force may be reduced by the feedback control if the control gain of K_h such as the PID parameters is large enough. However, the system becomes unstable if high control gains are selected [10].

The control objectives should satisfy good force tracking performance as well as reject the undesired dynamic forces caused by the user hand movements. Thus a self tuning fuzzy PID controller is proposed.

3. Force Control of the Haptic Feedback Device

The control algorithm in this paper extends the preceding works of PID control [3]. Where the PID parameter was selected for $K_h(s)$ indicated that it could reduce influence of gravity, inertia and friction. Experiments with the haptic teleoperation system also implied that if tune K_p, K_i, K_d, the tracking error performances can be improved.

Therefore a self-tuning fuzzy PID algorithm in Figure 3 is proposed for the $K_h(s)$ controller. PID parameters of $K_h(s)$ are selected in given ranges such as $k_p \in [k_{p\min}, k_{p\max}]$, $k_i \in [k_{i\min}, k_{i\max}]$, $k_d \in [k_{d\min}, k_{d\max}]$ and calculated as;

$$k_p = K_p(k_{p\max} - k_{p\min}) + k_{p\min}$$
$$k_i = K_i(k_{i\max} - k_{i\min}) + k_{i\min} \quad (9)$$
$$k_d = K_d(k_{d\max} - k_{d\min}) + k_{d\min}$$

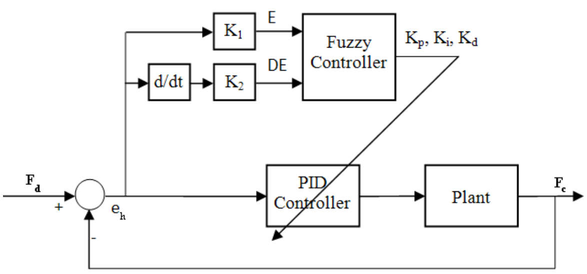

Figure 3. *Diagram of self-tuning fuzzy PID controller*

where K_p, K_i, K_d are outputs of fuzzy controller while the inputs are the force error $E = K_1 e_h$ and the force error change rate $DE = K_2 e_h$, with K_1, K_2 are positive constants.

The outputs of controller should be changed smoothly so symmetric Gaussian functions are selected for both input and output membership functions as;

$$f(x,\sigma,c) = e^{-\frac{(x-c)^2}{2\sigma^2}} \quad (10)$$

where parameters σ, c are selected in Table 1 based on the experiments of haptic teleoperation system. In which three linguistic terms of input variables are defined as P (positive), Z (zero), N (negative) and three linguistic terms of output variables are defined as S (small), M (medium) and B (big).

Table 1. *Parameters of membership function*

Parameter	Input			Output		
	N	Z	P	S	M	B
σ	0.6	0.7	0.6	0.2	0.2	0.2
c	-1	0	1	0	0.5	1

Table 2. *Fuzzy control rules*

DE	E		
	N	Z	P
N	S	S	M
Z	S	M	B
P	M	B	B

Table 3. *Control gain values*

Parameter	K_1	K_2	K_{pmin}	K_{pmax}	K_{imin}	K_{imax}	K_{dmin}	K_{dmax}
Value	0.4	0.1	0	4.5	0	0.06	0	0.04

This fuzzy controller is designed with 9 rules as shown in Table 2 to reduce the running time in a digital controller. Experiments have done to select the control gain values as shown in Table 3.

4. Experiment Results

A teleoperation system of 6-DOF haptic device with 6-DOF serial robot is shown in Figure 4. This control scheme extends the preceding works of teleoperation control system [3] and [9]. A digital controller dSPACE1103 with many useful interfaces such as ADC, DAC, Encoder, I/O, RS232 and RS485 is used to implement control algorithms. Moreover the dSPACE1103 can work with SIMULINK/MATLAB in real time to do experiments. The data can be recorded by ControlDesk software to evaluate and compare.

The teleoperation control system can be divided into two main parts: position control of slave serial robot and force control of master haptic device. The environment contact forces F_d are measured by a 6-DOF force sensor on the slave robot while contact forces F_c are measured by two 3-DOF force sensors on the haptic device. The force F_d is recognized as the desired force to the controller while the feedback is the contact forces F_c from the user hand. The output of $K_h(s)$ is the force command to the haptic device so it is converted into required torques by inverse transposed of Jacobian matrix. Six components of desired force F_d require six self-tuning fuzzy PID controllers separately.

The user contact forces F_c of the steering handle could track the environment contact forces F_d from environment well as shown in Figure 5. The trajectory x_r of the slave robot and the trajectory x_h of the haptic device are shown in Figure 6. These comparisons indicate that the tracking force performances could be well improved compared with the PID controller [3].

5. Conclusions

This paper presents a new force control model and proposes an impedance control algorithm using the self-tuning fuzzy PID controller for the haptic teleoperation system. The force control model including user hand contact force is developed and analyzed. The force control model shows that the user hand contact force F_c is induced by two inputs of F_d and x_u. This new force control model clearly shows the effect of the user hand and extends the previous works in [4-5].

The impedance control using fuzzy PID laws is designed to satisfy good tracking force performance as well as to reject the undesired dynamic forces caused by the user hand movements. All PID control gains works to improve transparency of haptic teleoperation system. Experiments show good performances in a manner that transparency is improved.

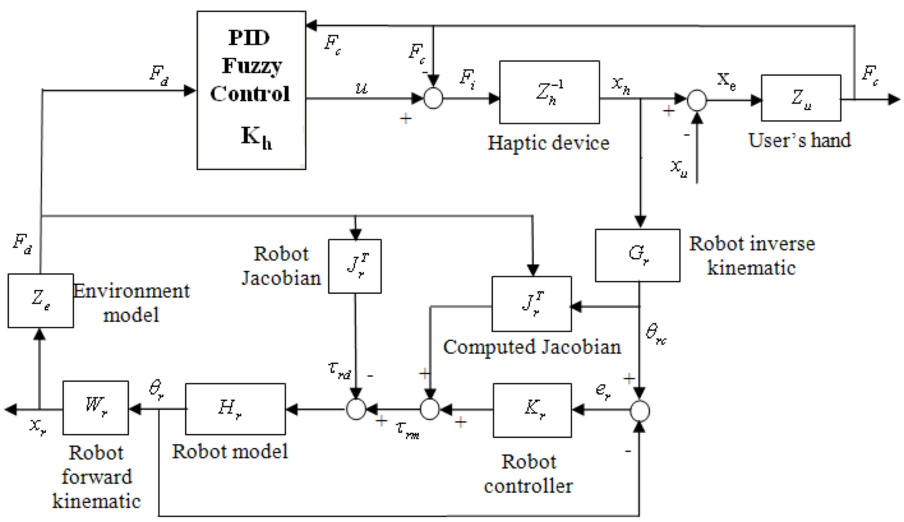

***Figure 4**. Teleoperation control system of a 6-DOF master haptic device with a 6-DOF slave serial robot*

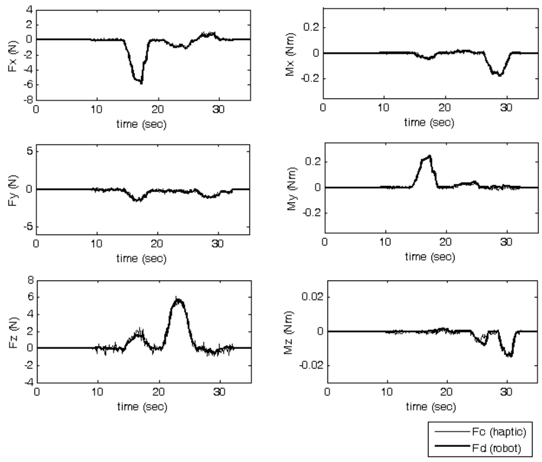

Figure 5. *Tracking force comparison of robot-haptic teleoperation system*

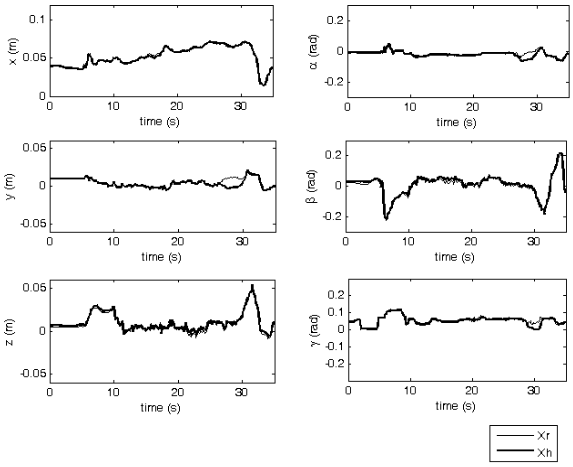

Figure 6. *Trajectory comparison of robot-haptic teleoperation system*

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