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Fuzzy PID Control Method for Internet-based Tele-operation Manipulators System

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Abstract

Trajectory tracking control problem for internet-based tele-operation system is researched in this paper. The control structure of master and slave tele-operation manipulators adapts bilateral servo control architecture with force deviation feedback. The simulation model of three degrees of freedom (3-DOF) manipulator is presented. In order to ensure the synchronization of positions of the master and slave manipulators, a fuzzy PID control method is proposed. This control algorithm is to adjust the three parameters of PID controller online by fuzzy control method. The contrast simulation experiments of PID and fuzzy PID control methods show that the proposed control method can effectively improve the force and position tracking performance and reduce time delay.

Keywords*: manipulator, tele-operation, fuzzy PID control, time delay*

1. Introduction

Tele-operation manipulator can replace human to work in the inaccessible or hazardous environments, and create more social value [1-5]. A typical tele-operation system is mainly composed of the human operator, the master manipulator, the slave manipulator, the communication channel and the work environment [6, 7]. The special work mode is that human operator sends control instruction to master manipulator, control instruction through a transmission medium sent to slave manipulator. Slave manipulator work according to the received instruction, and work state of slave manipulator is returned to master manipulator, operator make a decision according to the feedback information.

In 1965, ref. [8] firstly researched time delay of tele-operation manipulator. In this paper there was not force feedback, so time delay had no effect on stability of system. In [9], W. R. Ferrell pointed out that tele-operation manipulator with force feedback is unstable because of time delay, even if time delay is only a few tenths of a second. A main research work about tele-operation master and slave manipulators is to ensure the stability and operability of system in the time delay and complex environment. In the past 20 years, many researchers began to study the stability and operability of tele-operation master and slave manipulators system. To solve this problem, some researchers studied this problem from the point of view of control theory and method, and achieved certain results.

Bejczy [10] applied graphic reproduction thought of remote slave manipulator to put forward the concept of phantom manipulator. On this basis, Kototu [11] introduced force feedback into virtual manipulator. Spring effect was used to simulate environment and experiment was conducted at small time delay. Sheridan [12] applied Smith predictor to forecast the status of slave manipulator in tele-operation system. PD controller is used for adjusting slave manipulator. This control method can improve the system performances obviously and Smith prediction control method has became a broad class of time delay control method for tele-operation system [13-20]. Kikuchi [21] decomposed tasks into bilateral control, visual information and environmental dynamic forecasting and designed the three subsystems respectively. Baldwin [22] tried to apply Kalman filter to forecast the status of slave manipulator under low broadband. Bemporad [23] designed a forecast controller which can provide command sequences for communication interrupt. Aiming at the unpredictability and time varying characteristics of slave manipulator model and environment model in forecast display control

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method, Burdea [24] proposed a preview control system for tele-operation manipulators and this system had robustness for modeling error. Prokopiou [25] compensated the influence of time delay on system through forecasting the position and force of master manipulator. Experiment results show that this method is simpler to model for manipulator and environment, and the telepresence is stronger. Barth [26] combined forecast display control and system autonomy to obtain system data. Chen [27, 28] adopted neural network prediction method to predict the status of master manipulator and a good effect was achieved. Munir [29] combined wave variable method and Smith predictive control to restrain the influence of time-varying time delay on system. At the same time, the transparence of system was also improved. Mehmet [30] applied wave variable method to research multi-degree-of-freedom force feedback tele-operation system. This tele-operation system has two subsystems. The model of master manipulator controller is a three-degree-of-freedom joystick and the slave manipulator is a three degree of freedom Cartesian robot. These two subsystems are both build by SimMechanics modules of Matlab. The final simulation results show that wave variable can provide stable performance for unstable system when time delay is introduced.Yoshida [31] proposed a novel predictive control method for nonlinear multi-DOF tele-operation with time varying delay, parametric uncertainties of the robot model and uncertainties of remote environment. The proposed controllers consisted of three parts, Predictor, Trajectory generator and Adaptive controller. A control method which is combination of PD control based on the predictors and adaptive impedance control was adopted and it can achieve the position coordination and the static force reflection in certain conditions. Hashemzadeh [32] proposed a adaptive controller design scheme for nonlinear telerobotic systems with varying time delays where the delays and their variation rates are unknown. The designed controller can synchronize the state behaviors of the local and remote manipulators. Tele-manipulator dynamic model was given and Lyapunov stability of the the closed-loop teleoperation system was established. Experimental results showed the effectiveness of the proposed scheme. Zhang [33] proposed a H_∞ control method which can ensures the stability and performance between the master and slave manipulators under time delays and polytopic-type uncertainties. The design of the controller was performed by using Linear Matrix Inequality (LMI) optimization and H_∞ control theory. The stability of system and hign-quality performance were guaranteed based on this method. Simulations results demonstrated that such a tele-operation system can run in different working conditions.

A fuzzy PID control algorithm is proposed in this paper. This control algorithm can adjust the three parameters of PID controller online by fuzzy control method. SimMechanics model of manipulator is established and the proposed control method is researched on time delay simulation platform based on TrueTime software.

2. Research Method

2.1. SimMechanics Model of 3-DOF Manipulator

The control structure of master and slave tele-operation manipulators is bilateral servo control architecture with force deviation feedback (see in Figure 1). F_h is a force that the operator applies on the master manipulator, F_m is a reverse driving force that obtained by the master manipulator, F_s is driving force of slave manipulator, F_e is a force that the environment applies on the slave manipulator, X_m and X_s are the position of master and slave manipulators.

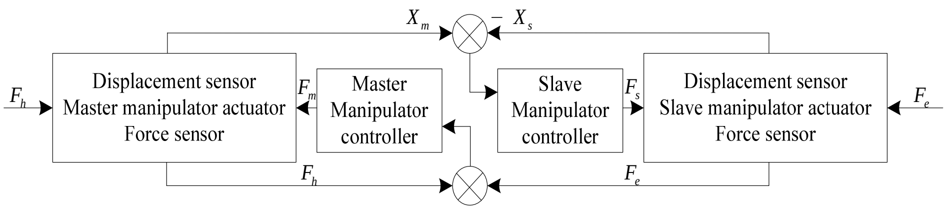


Figure 1. Bilateral servo control architecture with force deviation feedback

In order to realize that the master manipulator can track the position of slave manipulator, the position error signal between master manipulator and slave manipulator is used to drive the slave manipulator. In order to provide the force tele-presence to the operator, the force deviation signal between master manipulator and slave manipulator is used to drive the motion of master manipulator. The difference between the desired position of master manipulator and the actual position is used to simulate the force from human hands. In order to accurately control the position of the master manipulator, the force of the slave manipulator is introduced as the negative feedback; a closed loop control is formed. Actual position of master manipulator is namely the desired position of the slave manipulator, the position's error signal between master manipulator and slave manipulator is input into controller, after calculating by the control algorithm, the desired slave manipulator control force is obtained, and then a closed-loop control is formed, so as to control the movement of the slave manipulator.

2.2. SimMechanics Model of 3-DOF Manipulator

The model of 3-DOF manipulator was modeled by use of SimMechanics software (see in Figure 2). There have three revolute modules, three body modules, a machine environment module and a ground module. Revolute1, Revolute2 and Revolute3 represent three revolutes of manipulator. Joint Actuator1, Joint Actuator2 and Joint Actuator 3 are used to drive Revolute1, Revolute2 and Revolute3. Joint Sensor1, Joint Sensor2 and Joint Sensor3 are used to measure the angles of joints. Body Sensor is used to measure the trajectory of manipulator.

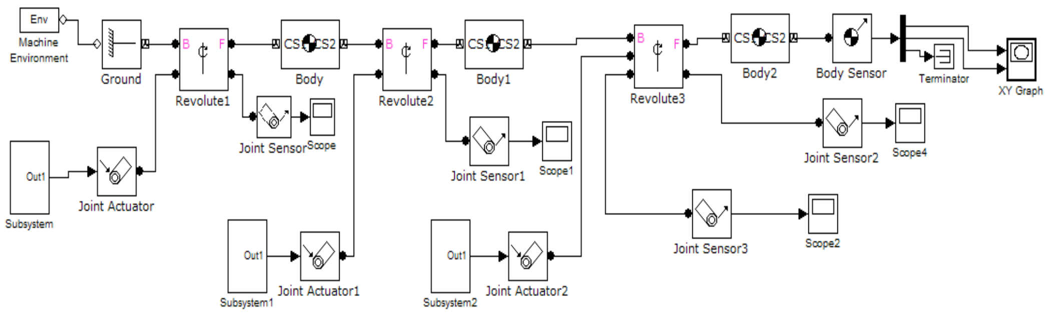


Figure 2. SimMechanics model of 3-DOF manipulator

2.3. Time Delay Simulation Platform based on TrueTime Software

Based on the control structure and principle of bilateral servo control architecture with force deviation feedback, we introduce the network control into the bilateral servo control system and design the time delay simulation platform based on TrueTime and Matlab/Simulink software. Comparator nodes of each sensor, controller and actuator are implemented by TrueTime kernel module; network module is implemented by TrueTime network module. The specific parameter setting is shown in Figure 3.

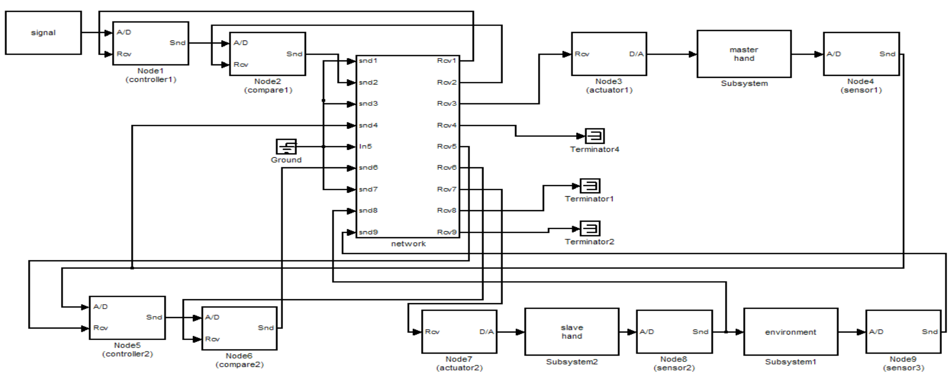


Figure 3. Simulation Diagram of Tele-operation Manipulators System based on TrueTime

Subsystem1 is environment model of system and its mathematical description is:

$$F_e = K_{p_s}(x_s - x_{obstacle}) + K_{d_s}\dot{x}_s \qquad (1)$$

Equation (1) expresses the relation of action force F_e and the position x_s of slave manipulator. K_{p_s} and K_{d_s} are environmental parameter, $x_{obstacle}$ is the position of obstacle.

2.4. Fuzzy PID Controller Design

The error *e* and the change of error *ec* are inputs of fuzzy PID controller. Three parameters P, I, D can be adjusted on line by fuzzy rule reasoning [34, 35]. The structure of fuzzy PID controller is showed in the Figure 4.

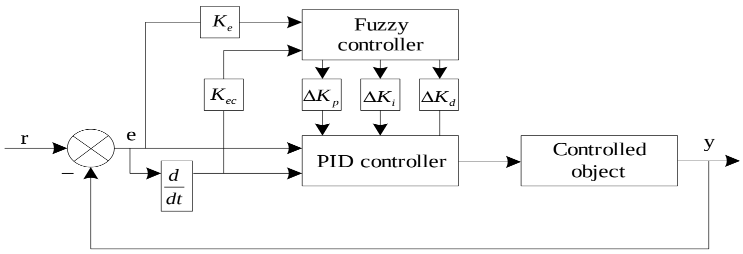
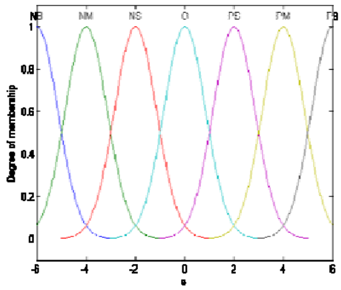


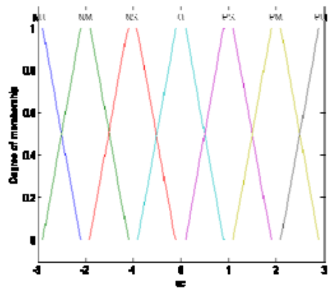
Figure 4. Control Structure of Fuzzy PID Control

The basic idea of fuzzy PID controller is to identify the fuzzy relationship between input and output, namely, is to identify the relation between error *e*, the change of error *ec* and three parameters K_p, K_i and K_d of PID controller, and then use the fuzzy rules to tune online these three PID parameters, and ultimately achieve the optimal control effect.

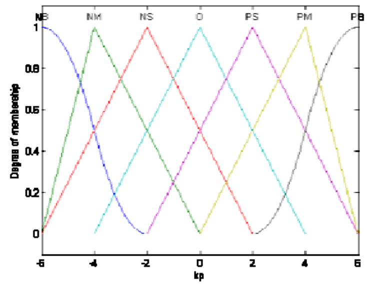
2.4.1. Fuzzification



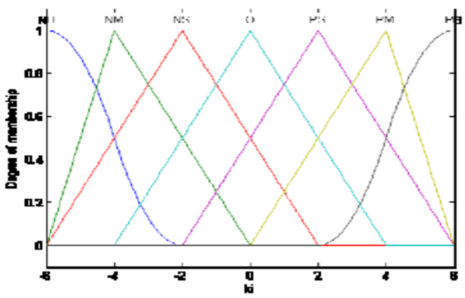
(a) Membership function of error *e*



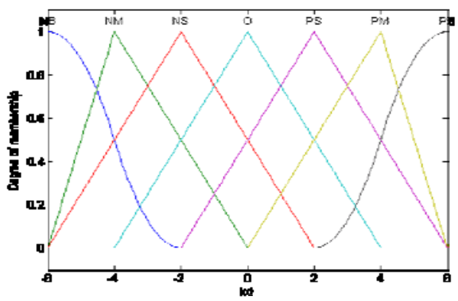
(b) Membership function of change of error *ec*



(c) Membership function of K_p



(d) Membership function of K_i



(e) Membership function of K_d

Figure 5. Curves of Membership Function of *e*, *ec*, ΔK_p, ΔK_i and ΔK_d

The input variables of fuzzy controller are error *e* and the change of *ec*, the output variables are correction parameters ΔK_p, ΔK_i and ΔK_d of PID control. The error *e* and the change of *ec* must be transformed into the form of fuzzy sets into fuzzy controller. There are defined as follow:

(1) The universe of error *e* is {-6, 4, -2, 0, 2, 4, 6}.

(2) The universe of change of error *ec* is {-3, -2, -1, 0, 1, 2, 3}.

(3) The universe of three output variables ΔK_p, ΔK_i and ΔK_d is {-6, -4, -2, 0, 2, 4, 6}

(4) The fuzzy subsets of input variables and output variables is {NB, NM, NS, O, PS, PM, PB}, these elements represent the negative big, negative median, negative small, zero, positive small, positive middle, and positive big respective.

The curves of membership function of *e*, *ec*, ΔK_p, ΔK_i and ΔK_d are shown in the Figure 5.

2.4.2. Fuzzy Reasoning

This paper adopts Mamdani fuzzy reasoning method, its implication relation is:

If *e*=A and *ec*=B then ΔK_p =C and ΔK_i =D and ΔK_d =F

The fuzzy control rules are:

(1) When *e* is bigger, K_p should be bigger, K_d should be smaller. This can speed up the system response speed. Make $K_i = 0$ at the same time, remove the integral effect, can avoid excessive overshoot.

(2) When *e* is middle, K_p should be smaller. This make system has small overshoot.

(3) When *e* is smaller, K_p and K_i should be bigger. This make system has good steady state performance. The value of K_d should be appropriate in order to avoid system oscillation near the equilibrium point.

The fuzzy value of correctional parameters ΔK_p, ΔK_i and ΔK_d can be obtained by fuzzy reasoning based on above fuzzy control rules (see in the Table 1).

Table 1. (a) Fuzzy Rule Table of ΔK_p

ec ΔK_p *e*	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PM	PM	PS	ZO	ZO
NM	PB	PB	PM	PS	PS	ZO	NS
NS	PM	PM	PM	PS	ZO	NS	NS
ZO	PM	PM	PS	ZO	NS	NM	NM
PS	PS	PS	ZO	NS	NS	NM	NM
PM	PS	ZO	NS	NM	NM	NM	NB
PB	ZO	ZO	NM	NM	NM	NB	NB

Table 1. (b) Fuzzy Rule Table of ΔK_i

ec ΔK_i *e*	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NM	NM	NS	ZO	ZO
NM	NB	NB	NM	NS	NS	ZO	NS
NS	NM	NM	NM	NS	ZO	PS	PS
ZO	NM	NM	NS	ZO	PS	PM	PM
PS	NM	NS	ZO	PS	PS	PM	PB
PM	ZO	ZO	PS	PS	PM	PB	PB
PB	ZO	ZO	PS	PM	PM	PB	PB

Table 1. (c) Fuzzy rule table of ΔK_d

ΔK_d (e \ ec)	NB	NM	NS	ZO	PS	PM	PB
NB	PS	NS	NB	NB	NB	NM	PS
NM	PS	NS	NB	NM	NM	NS	ZO
NS	ZO	NS	NM	NM	NS	NS	ZO
ZO	ZO	NS	NS	NS	NS	NS	ZO
PS	ZO	ZO	ZO	ZO	ZO	ZO	ZO
PM	PB	NS	PS	PS	PS	PS	PB
PB	PB	PM	PM	PM	PS	PS	PB

2.4.3. Defuzzification

In this paper, the weighted average method is adopted as defuzzification method, and its expression is:

$$X_0 = \frac{\sum_{i=1}^{n} X_i \cdot \mu(X_i)}{\sum_{i=1}^{n} \mu(X_i)} \tag{2}$$

Where X_i is fuzzy value, $\mu(X_i)$ is membership of X_i, X_0 represents the exact amount by the defuzzification method.

2.4.4. Fuzzy PID Control

Fuzzy PID control can be obtained by combining with PID control and fuzzy control method. Due to the introduction of the quantization factors and the scale factors, parameter adjustment method of fuzzy control is not the same adjustment method of PID control, control parameters tuning formulas of fuzzy control are:

$$K_p = K_{p_o} + k_1 * \Delta K_p \tag{3}$$

$$K_i = K_{i_o} + k_2 * \Delta K_i \tag{4}$$

$$K_d = K_{d_o} + k_3 * \Delta K_d \tag{5}$$

The parameters k_1, k_2 and k_3 are scale factors. The parameters K_{p_o}, K_{i_o} and K_{d_o} are initial PID parameters. The parameters ΔK_p, ΔK_i and ΔK_d are determined by fuzzy rules in the Table 1.

3. Results and Analysis

To verify the effectiveness of the proposed fuzzy PID control method, the contrast simulation experiments are researched in this section. Simulation experimental results are analyzed.

3.1. PID Control

Firstly, PID control method is researched. The tracking curve of force, the tracking error curve of force and the tracking curve of position are showed in Figure 6.

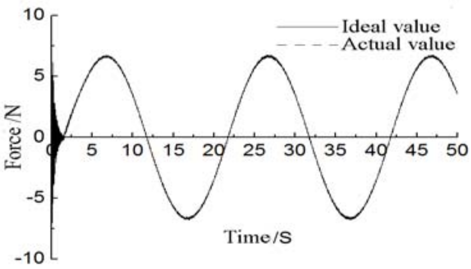
1. Analysis the force tracking result

In the Figure 6(a), it can be known that the tracking ability of tele-operation manipulator is good under the PID control method. But in the initial time, due to the impact force the initial force of slave manipulator has a larger oscillation. After about 2 seconds, slave manipulator began to be able to smoothly track master manipulator, the error is able to maintain between -

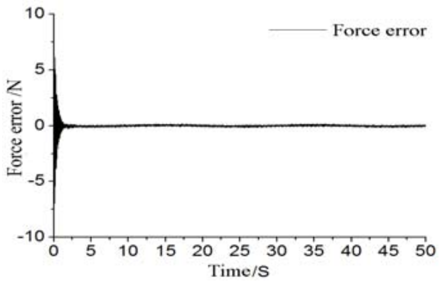
0.35 and 0.35. In the Figure 6(b), the curve has a high frequency and small amplitude oscillation. This shows that the tuning capability of the PID control algorithm is weak, the tracking performance of slave manipulator need to be improved.

2. Analysis the position tracking result

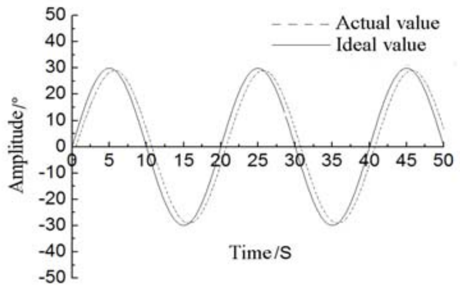
Let the master manipulator periodic motion, in the Figure 6(c) it can be seen that tracking performance of the slave manipulator is relatively stable, however its amplitude attenuation value is 1. This shows that slave manipulator does not have a good track the movement of the master manipulator, and time delay is also high and is about 0.5s. Time delay causes position error to become big, the position error is about 6.8 (see Figure 6(d)).



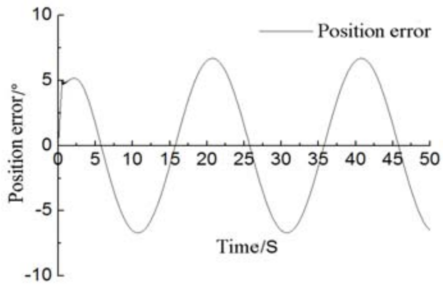
(a) Curve of force tracking



(b) Error curve of force tracking



(c) Curve of position tracking



(d) Error curve of position tracking

Figure 6. Simulation Results of PID Control Method

3.2. Fuzzy PID Control

Secondly, fuzzy PID control method is researched. The tracking curve of force, the tracking error curve of force and the tracking curve of position are showed in Figure 7.

1. Analysis the force tracking result

In the Figure 7(a), it can be known that the tracking ability of tele-operation manipulator is very good under fuzzy PID control method. Contrast to PID control method, the oscillation amplitude of error curve of force tracking is very small in the steady state. It also shows that the tuning ability of fuzzy PID algorithm is good. After about 2 seconds, slave manipulator began to be able to smoothly track master manipulator, the error is able to maintain between -0.22 and 0.22(see Figure 7(b)).

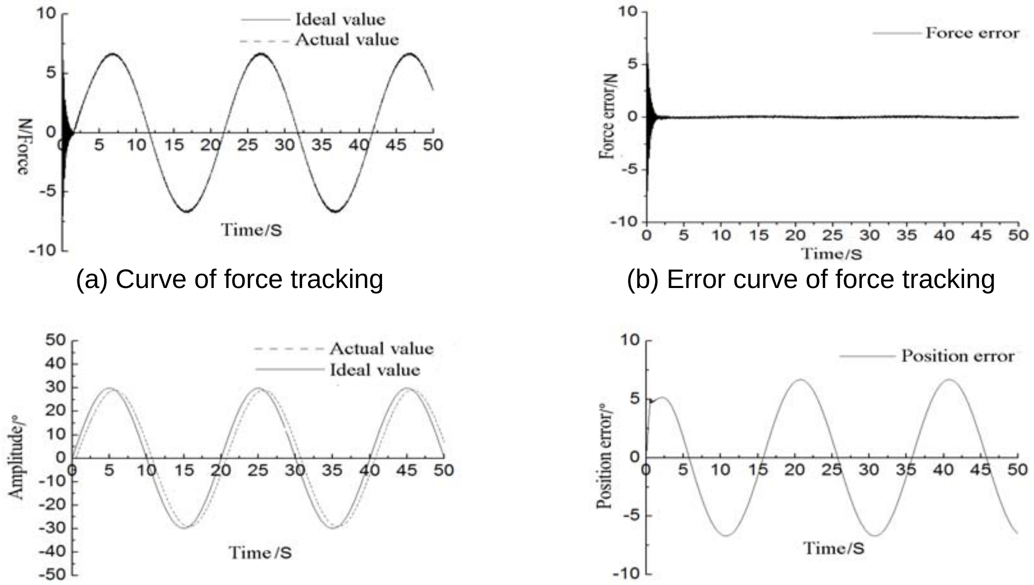
2. Analysis the position tracking result

Let the master manipulator periodic motion, in the Figure 7(c) and Figure 7(d) it can be seen that tracking performance of the slave manipulator is stable contrast to PID control method. The maximum error amplitude is less than 4.9, the time delay is about 0.4s.

Table 2 shows the comparison results of two methods of PID control and fuzzy PID control.

Table 2. Comparison Results of Two Control Methods

	PID control method	Fuzzy PID control method
Maximum error of force tracking result in the initial time	5.5	4.8
Maximum error of force tracking result in the steady state	0.35	0.22
Maximum error of position tracking result	6.8	4.9



(a) Curve of force tracking (b) Error curve of force tracking

(c) Curve of position tracking (d) Error curve of position tracking

Figure 7. Simulation Results of Fuzzy PID Control Method

4. Conclusion

In this paper, a fuzzy PID control method was proposed to control the internet-based tele-operation manipulators System. The control structure of master and slave tele-operation manipulators is bilateral servo control architecture with force deviation feedback. To verify the effectiveness of the proposed control method, time delay simulation platform based on TrueTime and Matlab/Simulink software was designed. The contrast simulation experiment between the proposed control method and conventional control method was researched. The results showed the proposed control method can effectively reduce errors of force tracking and position tracking of slave manipulator.

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