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Fuzzy PID Control and Simulation of Piezoelectric Ceramic Nanomanipulation System

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Abstract

With widely application of nanomanipulation, the design requirements of nanomanipulation control system is higher and higher. To improve the control precision of nano-components, it is important to do research on closed-loop control method for nanomanipulation. The piezoelectric ceramic actuator has the inherent characteristic of hysteresis, creep and nonlinear. Attocube is adopted as piezoelectric ceramic actuator in this system. Aiming at the designed nanomanipulation system based on Attocube, the closed-loop nanomanipulation control method based on fuzzy PID is studied. Based on the simplified modeling of piezoelectric devices and its displacement model, the controller of nano-manipulation system is designed and its simulation based on Matlab is conducted. Simulational results prove the effectiveness of the method.

Keywords: *Nanomanipulation; fuzzy PID; Attocube*

1. Introduction

When the control target varies from macro level to micro/nano level, phenomena and characteristics different from macro-control process will appear in the nanomanipulation process [1, 2]. Particularly the hysteresis, creep and nonlinear characteristic of nanomanipulation system based on piezoelectric actuator [3-6], which improves the requirements for the flexibility, reliability, efficiency, as well the control methods of the control system. Although the traditional PID control has the advantages of simple structure, strong robustness and fast dynamic response, there are still some deficiencies [7, 8]: Each output of the controller is related to the previous state, which leads accumulative deviation needing to be done every calculation accumulative, so the amount of calculation is large. The operation error and damages of operation object will be caused by the large operation displacement of the nanomanipulation end executor, for the PID output varies widely due to the fault as the output values corresponding with the actual position of the end actuator[9].When adjusting the PID parameters, increasing the the value of proportion parameter Kp can improve the rising velocity of the system, reduce steady-state error of the system, but simultaneously will cause the oscillation phenomenon in dynamic response process of the system, prolonging adjusting time of the system, affect the dynamic response of the system. Increasing differential coefficient Kd can effectively reduce the adjusting time and overshoot of the system. However, if Kd is too large, anti-interference ability of the workbench becomes poor, furtherly the stability of the nanomanipulation system will be impacted [10-13].

In conclusion, the traditional PID control can't guarantee dynamic response characteristics and steady- state accuracy of the nanomanipulation system at the same time. It is difficult to

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get accurate mathematical model of the nanomanipulation system. Aiming at the designed nanomanipulation system based on attocube actuator, the fuzzy adaptive PID control method is applied to design the nano-controller. The control system combines the advantages of traditional PID control and intelligent control system, based on the position feedback information during the motion of Attocube. PID parameters of the manipulation system can be corrected on line to meet the performance requirements of nanoscale manipulation platform.

2. Nanomanipulation system based on piezoelectric ceramic actuator (Attocube)

Structure diagram of the designed master-slave tele-nanomanipulaiton platform is shown in Figure 1. It is mainly composed of end nanopositioning platform, Attocube (piezoelectric ceramic drive), operation probe, slave nanomanipulation environment SEM, operator and master/slave PC.

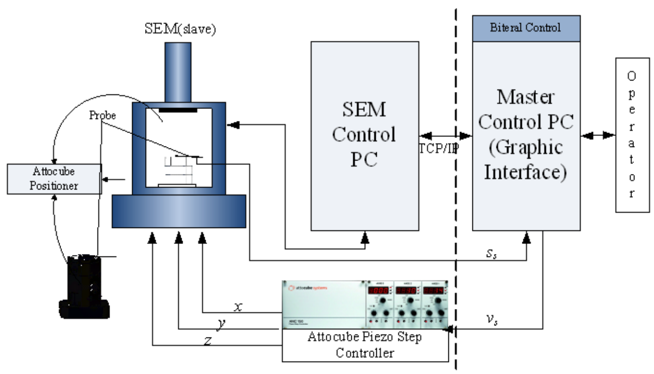


Figure 1. Structure of Master-Slave tele-nanomanipulaiton

3. Modelling of the Attocube nanomanipulation system

The performance of Attocube nanomanipulation device is affected not only by the characteristic of the material itself, but also by the driving power and the displacement characteristics of the end actuator. So the attocube nanomanipulation system modeling is divided into the drivinging device model and the end actuator displacement model [9].

3.1. Modelling of the Auttocbe driver

When driving voltage added to the Attocube, output of the Attocube and voltage applied on the driver have an approximate linear output relationship. Thus voltage amplification circuit of the Attocube piezoelectric ceramic nano-driver can be equivalent to link of charging and discharging of capacitor. Attocube and its driving power are simplified as electricity model shown in Figure 2.

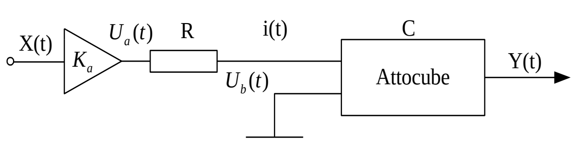


Figure 2. Attocube drive simplified model

With the simplified model above, the driving model of the Attocube driver is obtained:

$$G_1(s)=\frac{U_a(s)}{X(s)}\frac{U_b(s)}{U_a(s)}\frac{Y(s)}{U_b(s)}=K_a\frac{1}{RCs}K_b \tag{1}$$

where, K_b is the ratio of the *Y(s)* (Attocube displacement output) and $U_b(s)$ (the PZT material both ends input voltage).

The end actuator of the nanomanipulation system is the Attocube displacement device/positioner with Atomic-level precision developed by German Attocube System AG [10]. Through amplifier circuit of the internal drive power, the ratio of coefficient is $K_a=100$. In this paper the nanomanipulation system runs under the SEM. When the system runs in single-step, and the input voltage of Attocube is 10*V*, the output of the displacement ranges from 30*nm*to50*nm*, $K_b \approx 4nm/V$ .Then

$$\begin{aligned} G_1(s) &= K_a\frac{1}{RCs+1}K_b \\ &= 100\times 4.0\times 10^{-9}\frac{1}{1000\times 1.0\times 10^{-4}s+1} \\ &= \frac{0.4\times 10^{-5}}{s+10} \end{aligned} \tag{2}$$

3.2. Establishment of Attocube displacement model

When Attocube is drived by piezoelectric ceramic nano-deiver, its response to step input can be seen as a second order oscillation link. So the displacement model can be simplified as a second order system composed of three parts: quality, springs and damping (shown as in Figure 3) with the transfer function as:

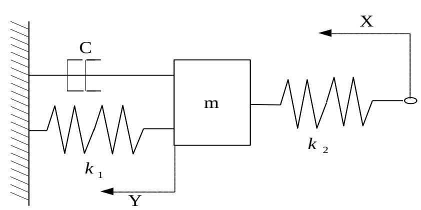


Figure 3. Simplified displacement model of nanopositioner

$$G_2(s)=\frac{k_s w_n^2}{s^2+2\zeta w_n s+w_n^2} \tag{3}$$

where w_n is the system natural frequency, ζ is the damping ratio. If $k_s=0.75$, $w_n=200$, $\zeta=0.497$, then the transfer function is shown as formula (4):

$$\begin{aligned} G_2(s) &= \frac{0.75\times 200\times 200}{s^2+2\times 0.497\times 200s+200\times 200} \\ &= \frac{30000}{s^2+198.8s+40000} \end{aligned} \tag{4}$$

So the overall transfer function of nano-driver system is **:**

$$G(s) = G_1(s)G_2(s) = \frac{0.4\times10^{-5}}{s+10}\times\frac{30000}{s^2+198.8s+40000} \quad (5)$$

4. Design of Fuzzy PID controller

Based on the actual system, the fuzzy adaptive PID controller is designed with two inputs and three outputs. The error *e* and error rate *ec* of the Attocube Z direction displacement acquired by the feedback image of SEM are the fuzzy inference inputs. ΔK_P , ΔK_I and ΔK_D are the fuzzy inference outputs. The controller structure is shown in Figure 4.

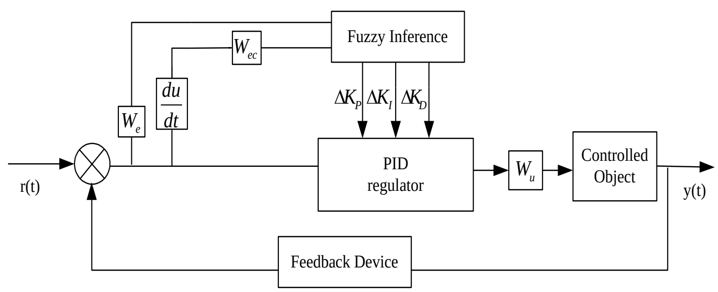


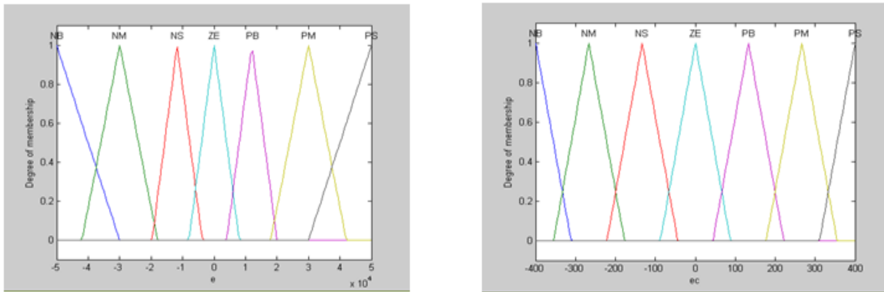
Figure 4. Structure of fuzzy adaptive PID controller

According to error *e* and error rate *ec* in the control process, the controller adjustments ΔK_P , ΔK_I , ΔK_D are aquaried by the fuzzy inference. The final parameters of fuzzy PID are calculated and determined by the following formula (K_{P0} , K_{I0} , K_{D0} is the initial value of PID):

$$\begin{cases} K_P = K_{P0} + \Delta K_P \\ K_I = K_{I0} + \Delta K_I \\ K_D = K_{D0} + \Delta K_D \end{cases} \quad (6)$$

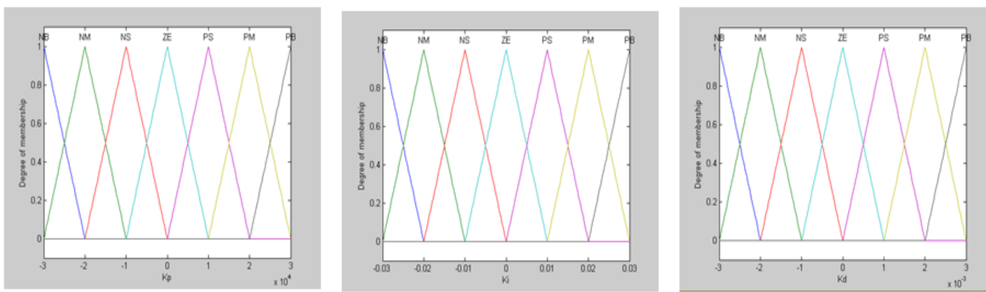
To improve the asymptotic stability of the system, the uneven regional partition method is selected when designing the membership function. The membership function of error *e* is showen in Figure 5(a). For the small error range, higher resolution of the fuzzy subset is selected and for the large error range, lower resolution of fuzzy subset is selected. The membership fuction of error rate *ec* use the uniform regional partition method. The membership function of *ec* is shown in Figure 5(b).

The fuzzy subset is defined as {Positive Big(PB), Positive Middle(PM), Positive Small(PS), Zero(ZE), Negative Small (NS), Negative Middle(NM), Negative Big(NB)}. The domain of *e* and *ec* is defined: [-5.0×10^{-4}, 5.0×10^{-4}] and [-4.0×10^{2}, 4.0×10^{2}] (position data with nanometer as unit is set to feedback once every 10 steps, and the control period is 2s). Based on the experimental values, domains of fuzzy PID parameters ΔK_P , ΔK_I and ΔK_D of the stable system are [-3.0×10^{4}, 3.0×10^{4}], [-3.0×10^{-2}, 3.0×10^{-2}] and [-3.0×10^{-3}, 3.0×10^{-3}]. The corresponding membership functions are shown in Figure 6.



(a) The membership function of *e* (b) The membership function of *ec*

Figure 5. The membership functions of *e* and *ec*



(a) Membership function of ΔK_P (b) Membership function of ΔK_I (c)Membership function of ΔK_D

Figure 6. The membership functions of ΔK_P , ΔK_I and ΔK_D

Based on the technical knowledge and practical experience of the operator, suitable fuzzy control rule table is established. The fuzzy control rule table of parameters ΔK_P , ΔK_I , ΔK_D are shown in Table 1 to Table 3.

Table 1. The fuzzy rule table of ΔK_P

K_P		*ec*						
		NB	NM	NS	ZE	PS	PM	PB
e	NB	PS	NS	NB	NB	NM	NM	PS
	NM	PS	NS	NB	NM	NS	NS	ZE
	NS	ZE	NS	NM	NM	NS	NS	ZE
	ZE	ZE	NS	NS	NS	NS	NS	ZE
	PS	ZE	ZE	ZE	ZE	ZE	ZE	ZE
	PM	PB	NS	PS	PS	PS	PS	PB
	PB	PB	PM	PM	PM	PS	PS	PB

Table 2. The fuzzy rule table of ΔK_I

K_I		*ec*						
		NB	NM	NS	ZE	PS	PM	PB
e	NB	PB	PB	PM	PM	PS	ZE	ZE
	NM	PB	PB	PM	PS	PS	ZE	NS
	NS	PM	PM	PM	PM	ZE	NS	NS
	ZE	PM	PM	PS	ZE	NS	NM	NM
	PS	PS	PS	ZE	NS	NS	NM	NM
	PM	PS	ZE	NS	NM	NM	NM	NB
	PB	ZE	ZE	NM	NM	NM	NB	NB

5. Simulation model of Nanomanipulation control system

To verify the effects of the designed fuzzy controller of the nanomanipulation system, Simulink tool in Matlab is adopted to create traditional PID and fuzzy PID control simulation model of the Attocube. It is shown in Figure 7, where K_{P0}、 K_{I0}、 K_{D0} are initial values, namely $K_{P0} = 4.5\times10^4, K_{I0} = 2.0\times10^{-2}, K_{D0} = 1.2\times10^3$.

Table 3. The fuzzy rule table of ΔK_D

K_D		*ec*						
		NB	NM	NS	ZE	PS	PM	PB
e	NB	NB	NB	NM	NM	NS	ZE	ZE
	NM	NB	NB	NM	NS	NS	ZE	ZE
	NS	NB	NM	NS	NS	ZE	PS	PS
	ZE	NM	NM	NS	ZE	PS	PM	PM
	PS	NM	NS	ZE	PS	PS	PM	PB
	PM	ZE	ZE	PS	PS	PM	PB	PB
	PB	ZE	ZE	PS	PM	PM	PB	PB

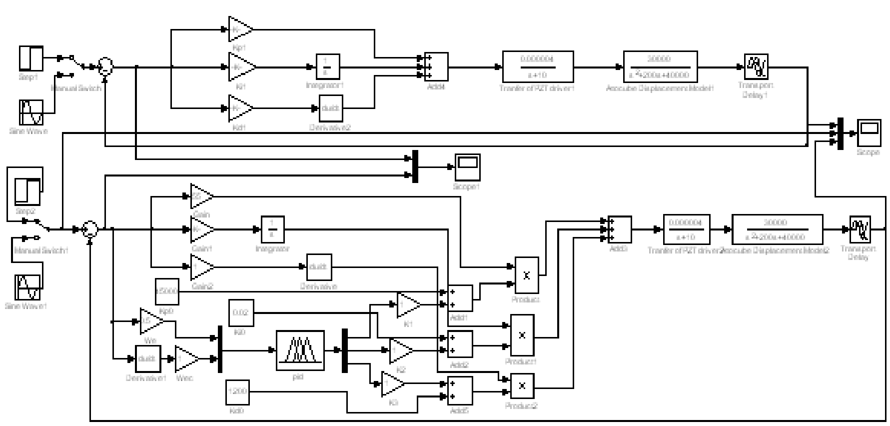


Figure 7. Simulink simulation model of the Attocube

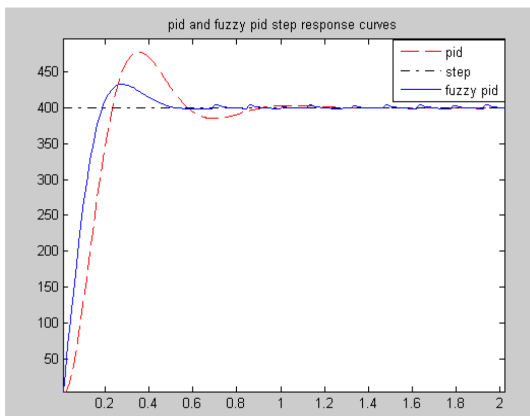
6. Analysis of Simulation Results

Based on the characteristics of nanomanipulation system under SEM, nanomanipulation process in fine positioning region is mainly studied. Simulation results of system dynamic performance with fuzzy PID control rule are analysed, including the output characteristics of step signal and sine signal.

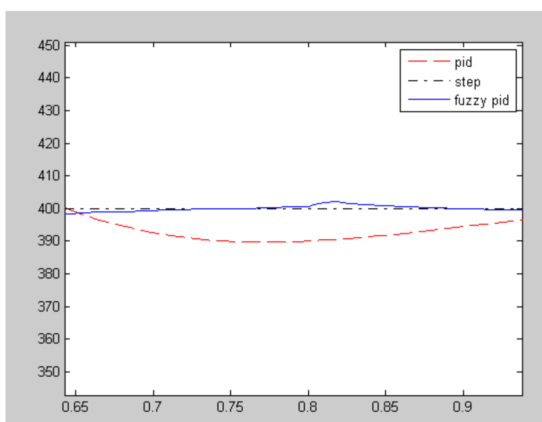
6.1. Characteristics comparison of step response

Simulations of the colsed-loop nanomanipulation system controlled by traditional PID control algorithm and fuzzy PID control algorithm are conducted separately. Compared with step response instruction of the actual system (control cycle is 2s, step amplitude is 400 nm), the response curves acquired arare shown as Figure 8.

It shows that both in dynamic and steady-state response stage, fuzzy PID has the better output characteristics. Fuzzy PID control can ensure the system stability time to be about 0.45s in a fast rise time. Simultaneously it can ensure the system overshoot volume $\sigma \leq 0.1nm$. The adjustment process error is shown in Figure 9. Therefore, the response speed and stability of the system have been improved by addoping fuzzy PID control algorithm.



(a) Dynamic response phase



(b) Steady-state response phase

Figure 8. Step response of traditional PID and fuzzy PID

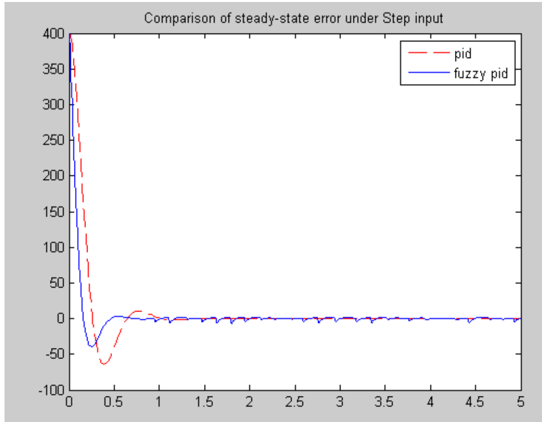


Figure 9. Steady-state error contrast under step signal

6.2. Characteristics comparison of sine signal tracking

In nanomanipulation system, the fast track ability of the Auttocube for the input signal is an important parameter of positioning system performance. Sine signal tracking curve under traditional PID and fuzzy PID control is shown as Figure 10. It shows that the sine curve tracking error under fuzzy PID control is less than 0.1s. In contrast, the tracking curve stability under traditional PID is poorer, and the error is greater than 0.15s. Therefore, the sine signal tracking effect under fuzzy PID control system is better than under traditional PID.

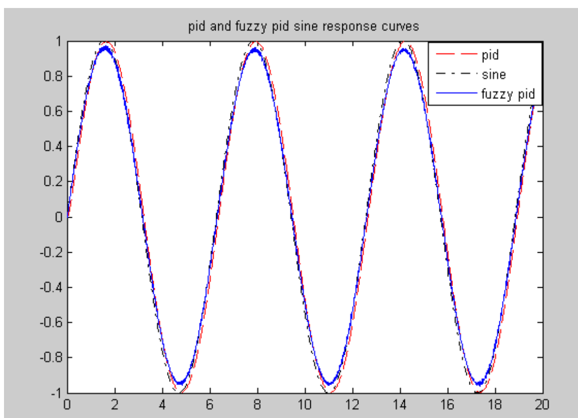


Figure 10. Sine signal tracking curve of the traditional PID and fuzzy PID

7. Conclusions

It can be concluded from the analysis of the fuzzy adaptive PID controller's simulation results: The designed fuzzy PID control method can effectively improve the static and dynamic response characteristics of nanomanipulation system. The overshoot is smaller, the response speed is faster, the settling time is shortened and the steady-state error is reduced. At the same time, compared with the sine signal input tracking curve, it shows the tracking effect is better under the fuzzy PID control. The introducing of fuzzy control algorithm can effectively improve the performance of the nanomanipulation system.

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