Application of Intelligent Fuzzy PID Control Algorithm in Large Astronomical Telescope Tracking System

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ABSTRACT

The telescope tracking system is one big-inertia, multivariable, nonlinear, complex and strong coupling mechatronic system which is disturbed by some nonlinear disturbance such as torque ripple, wind disturbance and the cable drag force during the tracking process. In order to suppress the nonlinear disturbance and improve the tracking precision in large astronomical telescope, this paper explores one intelligent fuzzy control algorithm which contains engineers' rich experimental experience and shows strong inductive ability. The simulation results show that the fuzzy controller is much stronger than traditional PID controller to suppress the nonlinear interference. The tests in the 1-meter telescope experimental platform also testify that it is very stable and the RMS of position tracking error is only 0.012″ in the super-low tracking speed 0.2″/s. While in the quick tracking speed, 6°/s with the acceleration $5°/s^2$, the RMS of position tracking error is only near to 1.8″. In conclusion, by the fuzzy control method designed in this paper, the dynamic response of the telescope tracking system has been improved effectively and the nonlinear interference has also been suppressed strong. What's more, the tracking accuracy has been improved greatly.

Keywords: Astronomical telescope, Direct drive, Nonlinear disturbance, Intelligent fuzzy control

1. INTRODUCTION

With the demand of larger diameter and higher tracking precision, there is a very huge challenge for the future telescope, while direct drive technology provides an effective solution to the more and more complex telescope tracking system[1]. It has been applied in the 8-10 meter large telescope, such as optical telescope VLT[2], Subaru[3], GTC[4] and radio telescope ALMA[5] . With the development of the direct drive technology, it is adopted in more and more telescopes with larger diameter, such as E-ELT[6], JELT[7], TMT[8] .

However, the direct drive tracking system of telescope is one complex mechanical control system which is big-inertia, multivariable and nonlinear. There is also some nonlinear disturbance such as torque ripple, wind load and friction torque

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disturbance during the tracking process. The contradiction between static and dynamic performance, tracking data and disturbance can't be solved fundamentally by traditional PID control algorithm. Especially in large astronomical telescope tracking system based on direct drive technology, the contradiction between overshoot and response of system is obvious with traditional PID control algorithm. This paper explores one intelligent fuzzy PID control algorithm to overcome the contradiction descripted above. In this method, the telescope tracking control system is designed using three closed loop PID control algorithm and the intelligent fuzzy algorithm is applied into position control loop. The control parameters of PID controller are adaptively adjusted by fuzzy controller based on Mamdani model. By constructing fuzzy control rules, fuzzy PID controller can revise the coefficient of P, I and D according to the instantaneous position tracking error and position tracking variety so that the telescope tracking system can always satisfy the tracking precision from slow speed to high speed.

2. **DESIGN OF FUZZY-PID CONTROLLER**

2.1 Tracking system model

During modeling, in order to make the simulation result more credible, some major parameters are based on the 1 meter telescope experimental platform shown in Figure 7, including the inductance of armature, the resistance of armature, back EMF constant, motor constant, rotor inertia and damping coefficient, and so on. This paper also takes major nonlinear disturbance such as friction torque, wind load and uncertainty of the model into consideration during designing the control algorithm.

Suppose the telescope tracking system meets the following conditions: the motor, the rotor shaft and the load have the same viscous friction coefficient and the stiffness of the system is big enough. In order to analyze the performance of the direct drive tracking system, the mathematical model is established as follows.

$$J\frac{d\theta^2}{dt}+B\frac{d\theta}{dt}+K\theta+T_w+T_f=T_e \tag{1}$$

Where, $\theta=\begin{bmatrix}\theta_1 & \theta_2\end{bmatrix}$ —Rotor mechanical angle; $T_e=\begin{bmatrix}T_1 & T_2\end{bmatrix}$ —Motor electromagnetic torque; J—Inertia of system converted to the motor rotor shaft; B—Viscous friction coefficient of system converted to the motor rotor shaft; K—Stiffness matrix; T_w —Wind disturbance torque; T_f —Friction torque.

Wind load disturbance is one of the most common nonlinear disturbance outside of the telescope system. Wind disturbance torque T_w in equation 1 is expressed by Davenport model in this paper, which consists of the static disturbance T_{const} and the dynamic disturbance $T_{\mathrm{var}y}$. T_{const} and $T_{\mathrm{var}y}$ are descripted respectively in equation 2 , 3.

$$T_{const}=1/2C_T\rho v^2AD \tag{2}$$

$$T_{\mathrm{var}y}=\frac{4K_0v^2(\rho vC_TAD)^2(fK_a/v)^2}{f[1+(fK_a/v)^2]^{(4/3)}} \tag{3}$$

Where, C_T —torque coefficient of wind disturbance; ρ —air density; v —wind speed; A —contact area; D —shaft radius perpendicular to contact area; K_a —Terrain roughness coefficient; $K_0=[0.4/\ln(z_r/z_0)]^2$; z_0 —local terrain roughness; z_r —reference height; f —frequency of the wind.

Friction disturbance is the most commonly nonlinear distance in the telescope tracking system, which can be expressed by LuGre model from equation 4 to equation 6.

$$T_f = \sigma_0 z + \sigma_1 \dot{z} + \alpha \dot{\theta} \tag{4}$$

$$\dot{z} = \dot{\theta} - \frac{\sigma_0 \left| \dot{\theta} \right|}{g(\dot{\theta})} z \tag{5}$$

$$g(\dot{\theta}) = F_c + \left(F_s - F_c\right) e^{-\left(\dot{\theta}/V_s\right)^2} + \alpha \dot{\theta} \tag{6}$$

Where, σ_0, σ_1 —dynamic friction coefficient; F_c —Coulomb friction; F_s —static friction; α —viscous friction coefficient; V_s —switching speed.

2.2 Fuzzy controller structure

The fuzzy controller designed in this paper is applied into position circle in the telescope tracking system, which consists of knowledge database, fuzzification, fuzzy inference and defuzzification. The position tracking error and the position tracking error variety are the two inputs of the fuzzy controller and the output of the controller is passed to the speed circle of the telescope tracking system. The structure of the fuzzy controller is shown in Figure 1.

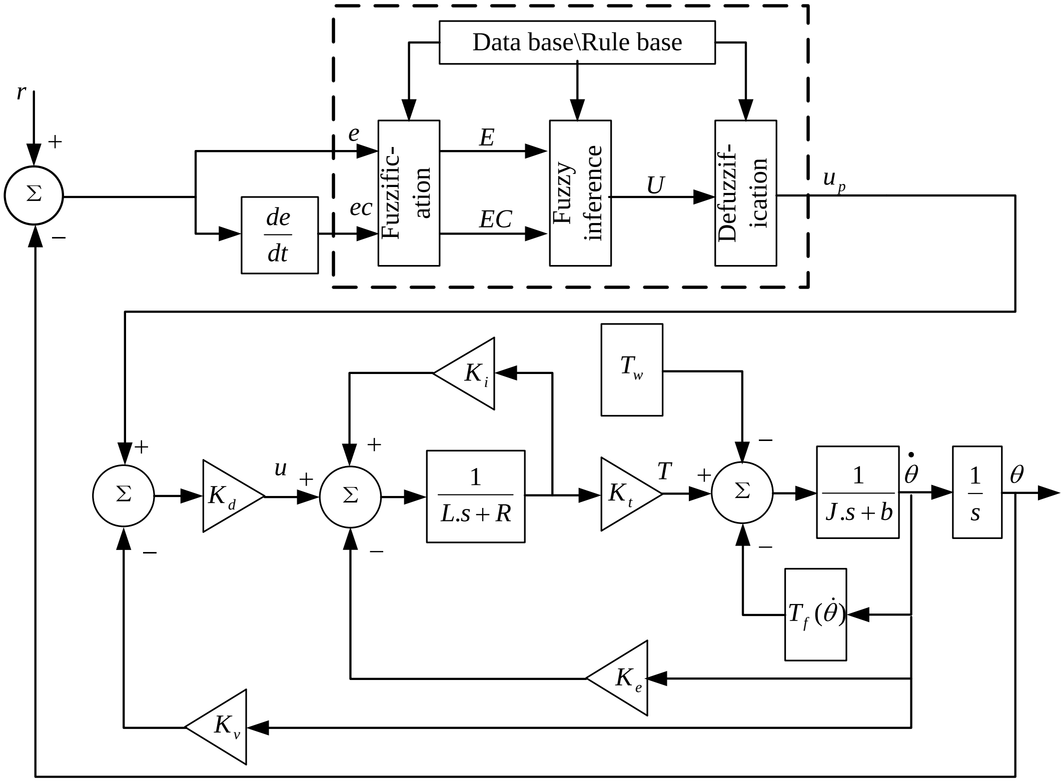


Fig1. Framework of fuzzy controller

The transform functions from the output u of speed circle to torque T and from torque T to speed $\dot{\theta}$ are expressed respectively in equation 7 and in equation 8.

$$T=\frac{K_t}{Ls+R}\left(u-K_e\dot{\theta}\right) \tag{7}$$

$$\dot{\theta}=\frac{1}{Js+b}\left(T-T_w-T_f\right) \tag{8}$$

Suppose $x_1=\theta$, $x_2=\dot{\theta}$ and $x_3=T$, the state space equation can be descripted as follows.

$$\dot{x}_1=x_2 \tag{9}$$

$$\dot{x}_2=\frac{1}{J}\left(x_3-T_w-T_f-bx_2\right) \tag{10}$$

$$\dot{x}_3=\frac{1}{L}\left(-K_eK_tx_2-Rx_3+K_tu\right) \tag{11}$$

Where, L —inductance of the motor armature circuit; R —resistance of the motor armature circuit; K_t —torque coefficient of motor.

2.3 Fuzzification

In order to use fuzzy theory, the first step is to convert the accurate value to fuzzy value, which is called fuzzification. In this paper, the two input of the fuzzy controller are the position tracking error and the change of position tracking error. And the input will be mapped to the domain of membership function. Now the membership function has been split into 7 discrete domains, which are expressed as {NB, NM, NS, NO, PS, PM, PB}. The membership functions of position tracking error and position tracking error variety are designed in Figure 2.

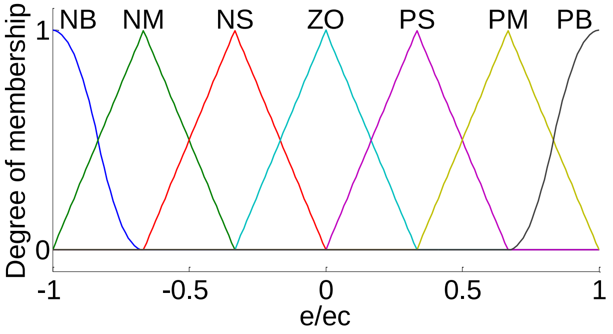


Fig2. Membership function of e and ec

2.4 Fuzzy rules

The fuzzy rules define the mapping relation from the input to the output, which is the kernel function of the fuzzy controller. And the fuzzy rules mostly affect the performance of the controller. In this paper, the fuzzy rules are designed on the basis of the experience of engineers and the knowledge about control engineering. Based on a lot of experimental data, a fuzzy rule table which consists of two more important parameters Δk_p and Δk_d is designed in Table 1.

Tab1. Fuzzy control rules of Δk_p and Δk_d

E	EC						
	NB	NM	NS	ZO	PS	PM	PB
NB	PB/NB	PM/NM	PS/NS	ZO/ZO	NS/PS	NM/PM	NB/PB
NM	PM/NM	PM/NM	PS/NS	ZO/ZO	NS/PS	NM/PM	NB/PB
NS	PS/NS	PS/NS	PS/NS	ZO/ZO	NS/PS	NM/PM	NB/PB
ZO	ZO/ZO	ZO/ZO	ZO/ZO	ZO/ZO	NS/PS	NM/PM	NB/PB
PS	NS/PS	NS/PS	NS/PS	NS/PS	NS/PS	NM/PM	NB/PB
PM	NM/PM	NM/PM	NM/PM	NM/PM	NM/PM	NM/PM	NB/PB
PB	NB/PB	NB/PB	NB/PB	NB/PB	NB/PB	NB/PB	NB/PB

2.5 Defuzzification

In the fuzzy rule table above, the input and output are all fuzzy value, which can't be applied to control the tracking system. So, the output of the fuzzy controller should be converted to accurate value and the most common method is the centre-of-gravity(COG) method. Using COG method, the surface charts of parameters Δk_p and Δk_d are plotted in Figure 3.

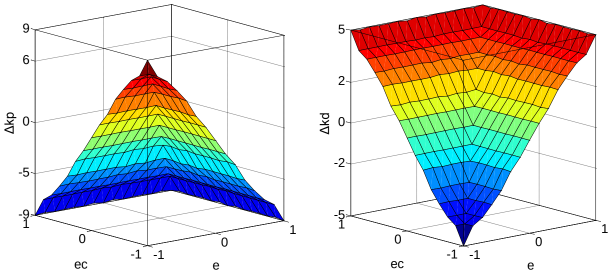


Fig3. Surface charts of Δk_p and Δk_d

3. SIMULATION

The simulation is based on the telescope experimental platform shown in figure 7 and the major parameters are listed in table 2. During simulation process, the acceleration of the tracking system is limited to 5 °/s^2 and the max speed is limited to 6 °/s. The results of the simulation in terms of step response are shown in Figure 4 and 5, respectively at 0.2″ and 90 °.

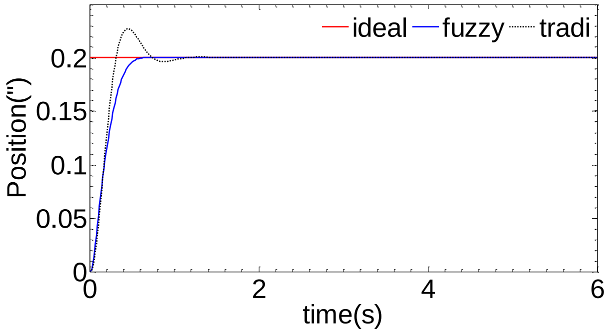


Fig4. Step response curve at 0.2″

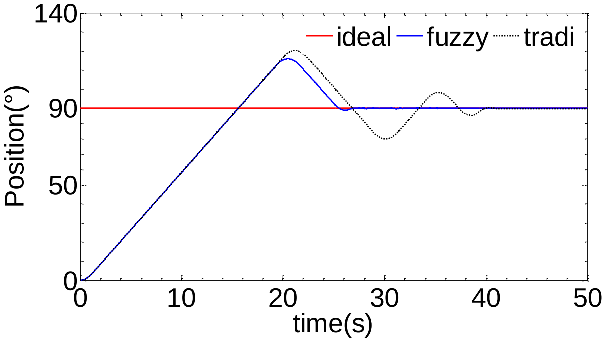


Fig5. Step response curve at 90 °

In Figure 4 and 5, there are smaller overshot, faster response, and better dynamic performance under the fuzzy controller than traditional PID controller. The contradiction between overshoot and response of the tracking system has been solved well. At the same time, much higher tracking accuracy is gotten in the telescope tracking system.

In order to analyze how fuzzy controller work out for nonlinear disturbance including wind disturbance and friction disturbance, the wind model Davenport and the friction model LuGre are took into consideration. Figure 6 shows the results of simulation for 1 °step response where the disturbance model described above works.

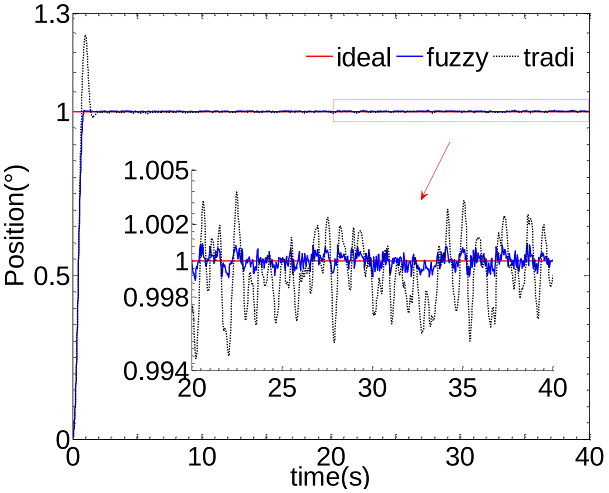


Fig6. Response curve of nonlinear disturbance test

In Figure 6, the overshot of the tracking system controlled by fuzzy controller is smaller than traditional PID controller and the stabilization time is shorter. When position tracking is stable from 20s to 40s, we will see the effect from wind load on position tracking with fuzzy controller is smaller than traditional PID controller, which proves that fuzzy controller has stronger anti-disturbance ability of nonlinear disturbance than general PID controller.

4. EXPERIMENT

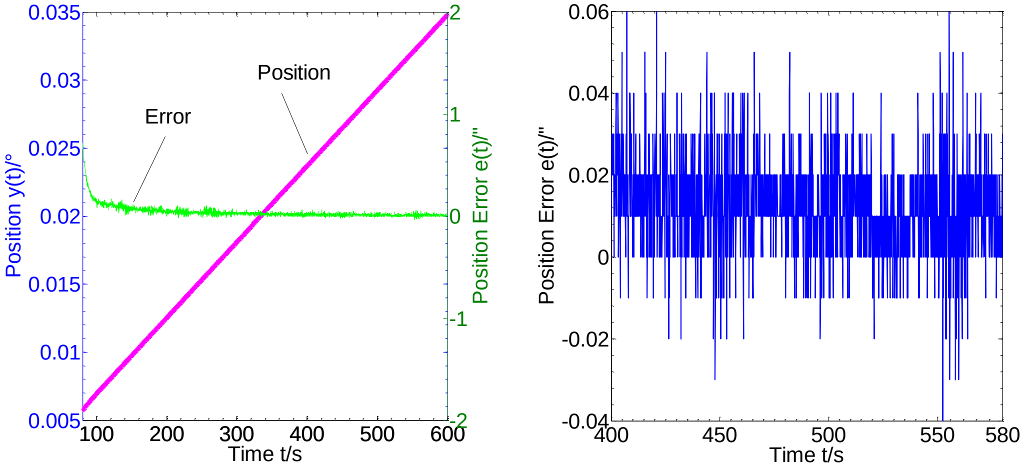
The telescope experimental platform is shown in Figure 7, which is driven by direct drive motor and whose mechanical structure is horizontal. The electrical parameters and the torque parameters of the 1 meter telescope experimental platform are shown in Table 2.

Fig7. Telescope experimental platform

Tab2. Parameter of telescope experimental platform

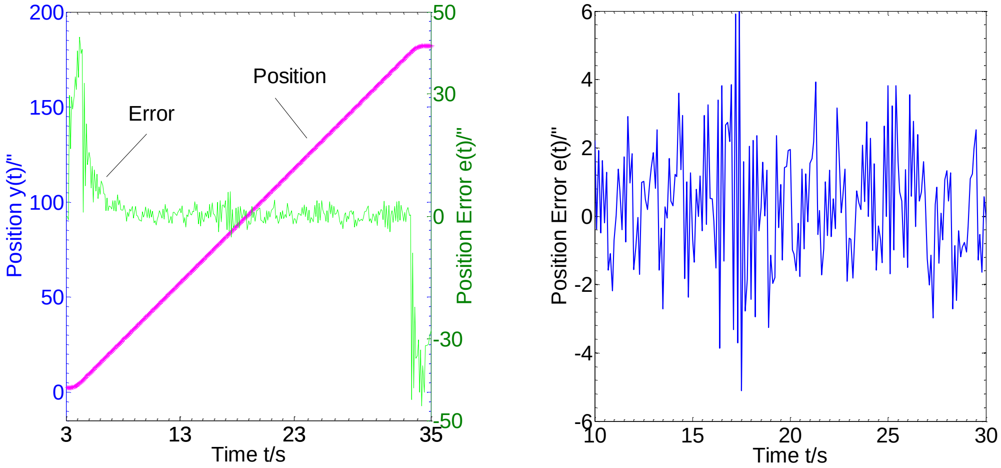
Parameters	Value
Terminal resistance	3.27 Ohm
Terminal inductance	39.3 mH
Damping coefficient	15N/(m/s)
Motor constant	17.9Nm/Sqrt(W)
Back EMF constant	22.9V/(rad/s)
Rotor inertia of AZ	1103.85kg.m^2
Rotor inertia of ALT	635.54kg.m^2

During test process, the acceleration of the tracking system is limited to 5 °/s^2 and the max speed is limited to 6 °/s the same as simulation process. The results of the test in terms of ramp response are shown in Figure 8 and Figure 9, respectively at 0.2″ and 6 °.



(a)Ramp response at 0.2″/s (b)Steady-state error

Fig8. Ramp response at 0.2″/s and positional steady-state error



(a)Ramp response at 6 °/s (b)Steady-state error

Fig9. Ramp response at 6 °/s and positional steady-state error

The tests in the telescope experimental platform also testify that it is very stable and the RMS of position tracking error is only 0.012″ in the super-low tracking speed 0.2″/s. While in the quick tracking speed, 6°/s with the acceleration 5°/s^2, the RMS of position tracking error is near to 1.8″.

5. CONCLUSION

The simulation and the test results in 1-meter telescope experimental platform show that the general PID control method will lead to large overshoot and adjustment time is too long, which is especially apparent in the telescope direct drive tracking system with such a huge inertia. By comparison, the intelligent fuzzy PID control method accelerates the dynamic response of telescope tracking system and improves the anti-disturbance ability of nonlinear disturbance. Such tracking system based on fuzzy PID control algorithm can not only satisfy the requirements for the mount driving servo system in large astronomical telescopes that high precision and ultra-lower velocity is needed but also keep high precision when it is commanded to move to the target location with high speed. In addition, the nonlinear interference has also been suppressed strong.

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