Original Research Article

Design and application of fuzzy PID controller based on MATLAB

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ABSTRACT

In an era where the development of intelligent technology is a pivotal force propelling economic advancement, enhancing production efficiency, diminishing costs, and reshaping daily life, the field of intelligent vehicle control technology has garnered significant attention within the automotive sector. This research tackle the complex challenges inherent in intelligent vehicle control by integrating a fuzzy PID algorithm, which merges the principles of fuzzy control theory with the established framework of classical PID control. This innovative approach is designed to bolster the adaptive capabilities and speed regulation of vehicles under diverse and challenging road conditions, thereby refining control performance. Through comprehensive analysis of the current landscape and technological advancements in intelligent vehicle control systems, coupled with rigorous MATLAB/Simulink simulations and real-world testing, the study demonstrates that the fuzzy PID algorithm exhibits superior performance in dynamic response, robustness, and accuracy compared to traditional PID methods. Consequently, it markedly enhances the precision and stability of speed control in intelligent vehicles, providing a groundbreaking perspective and practical methods for the enhancement of intelligent vehicle control systems with considerable application potential.

Keywords: PID; Fuzzy PID; intelligent car; MATLA

1. INTRODUCTION

In today 's world, the development of science and technology and economy is growing exponentially, and artificial intelligence technology has penetrated into people 's daily life. As an important application of intelligent technology, intelligent assisted driving has made great progress at home and abroad. With the continuous breakthrough of autonomous driving technology, the intelligent vehicle and automobile industry have also entered a new era of development. If the development of science and technology is compared to the growth of a baby, traditional technology constitutes the baby 's bones, manufacturing capacity constitutes the baby 's muscles, and the soul that drives the entire baby 's body is innovative intelligent design. Deeper mental activity is far more efficient than simple physical activity. The rapid development of the times must be inseparable from innovative intelligent design. Intelligent facilities have emerged as the times require, infiltrating and changing our lives. In the context of the development of the global economy and the intensification of competition, enterprises need to find the core competitiveness of products, seek means to reduce costs, and improve their competitiveness. In this context, intelligent technology has been paid more and more attention.

In the automotive industry, under the background of the rapid development of the intelligent assisted driving automotive industry, the control of intelligent vehicles has become one of the research hotspots in the current automotive industry. Because of the rapid development of urbanization, the road network is becoming more and more complex, the number of vehicles passing through the road is increasing, and the traffic congestion is becoming more and more serious; when there are more vehicles, it will not only cause traffic congestion, but also cause frequent traffic accidents. In particular, accidents on expressways will cause great losses to people 's lives and property. Therefore, the study of intelligent vehicle control technology can greatly reduce the incidence of traffic accidents.

The control technology of intelligent vehicle can be traced back to the development of automotive electronic technology in the early last century. From the initial simple electronic components, such as on-board radios and in-vehicle lighting controllers, to today 's advanced driver assistance systems (ADAS) and autonomous driving technology, automotive electronics technology has undergone decades of development. PID controller is one of the most widely used control algorithms in intelligent vehicle control technology. PID controller [1] first appeared in the field of power engineering control at the end of the 19th century, and it was not widely used in automobile control until the 1980s. With the continuous development of computer technology and control theory, PID controller is also evolving rapidly. In the mid-1980 s, the digital PID controller [2] appeared, which laid the foundation for the realization of PID controller. Subsequently, the adaptive PID controller [3], microprocessor PID controller and other further optimization and its implementation. In recent years, PID controllers also face some challenges. For example, when the control system has strong coupling such as nonlinearity and time-varying, a single PID controller is often difficult to meet the requirements of accuracy and stability. Therefore, there are some improved algorithms in the field of control theory, such as fuzzy PID controller [4], neural network PID controller, model predictive controller, etc. These methods can optimize the parameters of PID controller and dynamic characteristics for specific scenarios. Therefore, this topic is to study the control effect of traditional PID and fuzzy PID [5] on smart cars by using MATLAB simulation technology in a scenario such as smart cars.

2. MATERIAL AND METHODS

MATLAB is an advanced technology computing software which is widely used in scientific computing, engineering design, education and other fields. It has many excellent features, such as user-friendly interactive development environment (IDE), first-class data visualization and drawing tools and powerful programming language. MATLAB is a data-driven programming language, which can be used to deal with large data sets and matrix operations. At the same time, it can be integrated with many other common applications and tools. In addition, MATLAB also includes many convenient tools for specific applications, such as signal processing, audio processing, statistical analysis, optimization and control system design toolbox. These toolkits provide application-specific functions and tools to help users research and solve problems more efficiently. The product mainly includes two parts: MATLAB and Simulink.

2.1 PID controller definition

PID controller is composed of three parts: proportional control, integral control and differential control. Its role is to adjust the system error, and ultimately achieve the steady state of the system, and greatly reduce the difference between the cycle time or outside the cycle time [6]. PID controller is a very useful controller, which is widely used in various control tasks in different fields.

(1) Proportional control is the first and simplest part of PID controller [7]. Its basic principle is to control and adjust according to the error of the system. The greater the error from the target, the stronger the intensity of the output signal of the controller. The form of proportional control is a proportional coefficient, which can be selected by certain rules and experience.

(2) Integral control is the second part of PID controller, which can improve the effect of proportional control and increase the stability of control. Its basic principle is to adjust the error accumulation over time, and to calculate and accumulate the difference between the output signal of the controller and the target signal [8]. The form of integral control is to add an integral term in the controller, and adjust the intensity of the output signal of the integral control through a coefficient.

(3) Differential control is the third part of PID controller, also known as differential control. It can respond to rapid system changes and reduce the transition time of the system. The basic principle of differential control is to control the system error by the derivative term in the controller output signal.

2.2The principle of PID controller

In order to realize the PID control system, we first need to understand the principle and mathematical model of the PID control system. PID controller is a closed-loop controller for feedback control, which has three control modes: proportional, integral and differential. The output of the PID controller is related to the control error. The actuator can be controlled by comparing the difference between the actual value and the target value, so that it can output controllable and stable control signals, so as to realize the control of the controlled object [9]. The mathematical model of PID controller can be described by a formula (2.1):

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{de(t)}{dt} \quad (2.1)$$

In the formula, u (t) is the output signal of the controller, e (t) is the difference between the actual value and the expected value, and Kp, Ki and Kd represent the proportional, integral and differential coefficients respectively. By adjusting the Kp, Ki and Kd coefficients, the response speed, stability and anti-interference performance of the controller can be changed, so as to realize the control system that meets the requirements.

2.3simulink simulation

Simulink is a visual tool for model design, simulation and implementation of dynamic systems in MATLAB. Simulink mainly relies on graphical block-based graphical description for model construction and simulation. It allows users to visually create or modify the system directly and manipulate the parameters of various components and components, so as to obtain realistic and efficient simulation results. Simulink has a large number of modules, such as system modeling, signal and image processing, dynamic system modeling, etc., which can be widely used in aerospace, automobile, ship, engineering, energy and other fields. It has great application and advantages in system modeling, simulation and other aspects.

By using Simulink for simulation, it is easy to model and debug the motor control system. Compared with the traditional trial and error method, Simulink provides intuitive visualization tools and flexible parameter adjustment functions, which greatly saves the time and cost of setting parameters. In terms of motor control, Simulink 's PID control structure diagram (shown in Fig.1) facilitates controller design and simulation. By establishing the simulation model and inputting the unit step signal, the complex motor control system can be simulated and analyzed [10]. During the simulation process, the user can freely adjust the simulation parameters, monitor the system response and the performance of the controller, and optimize them.

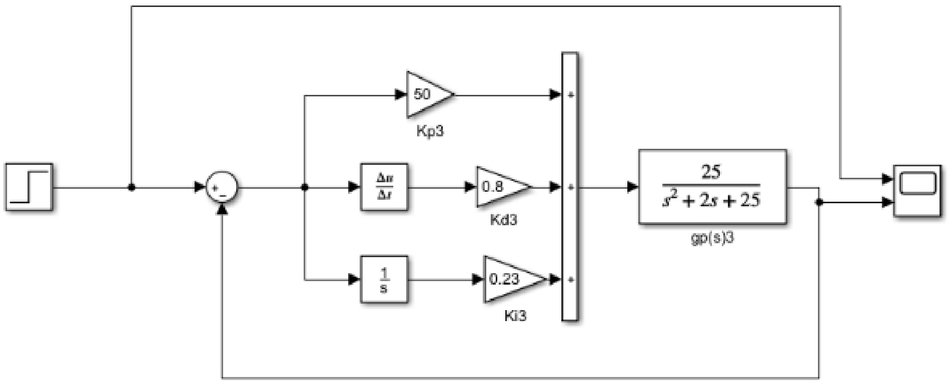

Fig. 1.Simulink simulation of PID controller

2.4PID parameter tuning

In PID control, it is important to achieve the best performance of the control system by properly adjusting the values of these three parameters. The three parameters are proportional coefficient (Kp), integral coefficient (Ki) and differential coefficient (Kd), which correspond to the three basic control behaviors of the controller, reflecting the response speed, stability and anti-interference of the controller. The specific role is as follows :

The magnification of the proportional coefficient Kp control error is the most basic proportional controller in the control loop. The larger the proportional coefficient Kp, the faster the response speed of the controller to the error, but at the same time, it will also increase the stability of the system, oscillation and even instability such as oscillation.

The role of the integral coefficient Ki is to eliminate the steady-state error of the control system and to compensate for slower changes. In general, a larger integral coefficient can reduce the steady-state error of the controller, but if the integral coefficient is too large, the system may have integral saturation, resulting in system failure [11].

The differential coefficient Kd is used to weaken the sensitivity of the controller output to interference and suppress the fast response of the system. The larger the differential coefficient Kd, the stronger the controller 's ability to control interference, but too large differential coefficient will also reduce the stability of the control system, and even cause instability of the system in some cases.

In order to obtain more accurate simulation parameters, we use the stable boundary method (Table 1) to tune the PID parameters. This method finds the optimal parameter configuration by performing trial control on the stable boundary of the system within a certain range. The stable boundary method has the advantages of high precision, fast efficiency and good stability. It has a very good effect on the control and optimization of the system under various working conditions.

Table 1. Parameter adjustment

regulating law	parameter tuning		
	Kp	Ki	Kd
P	0.5Kp		
PI	0.455Kp	0.535Kp/T	

PID	0.6Kp	1.2Kp/T	0.075KpT

The specific steps of using the stable boundary method to adjust the PID parameters are as follows:

(1) The integral coefficient Ki and the differential coefficient Kd are set to 0, and the proportional coefficient Kp is set to a smaller value to make the system operate stably.

(2) Gradually increase the proportional coefficient Kp until the system appears stable oscillation. At this time, the critical oscillation gain Kp is recorded.

(3) According to the empirical formula of Table 1, the corresponding PID parameters are set, and then the Simulink simulation is carried out.

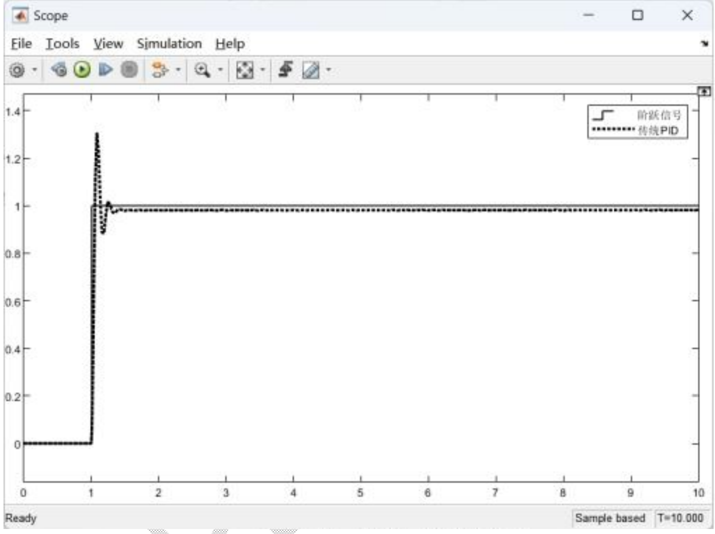

Fig.2. Step response of PID controller

After repeated parameter tuning, the final parameters of the PID are:Kp = 50, Ki = 0.8, Kd = 0.23, and the output waveform is the most stable. It can be seen from Fig.2 that the system can respond quickly. For incremental PID control, such performance indicators have been able to achieve the purpose of stable control of smart cars.

2.5Establish fuzzy control rules

In PID control, the system deviation refers to the difference between the actual output and the expected output, which is the so-called error. In general, the PID controller measures the error between the system output and the desired output, and calculates and adjusts the output signal of the controller according to the size of the error, so that the system output is as close as possible to the desired output. If the system deviation is large, it is necessary to use the proportional coefficient Kp to adjust the response speed of the controller to the error. If the system deviation is small, it is necessary to use the integral coefficient Ki to reduce the error, or use the differential coefficient Kd to suppress the oscillation of the system. The controller needs to use these three coefficients flexibly according to the actual situation and system characteristics to achieve the control objectives.

Therefore, the key to the success of the fuzzy PID control system is how to quickly and accurately realize the self-adjustment of the three coefficients of the PID, and fuzzy adaptive control of the speed of the intelligent vehicle [12].

The control system must realize the real-time correction and adjustment of the three parameters of proportional, integral and differential of PID according to the following reasoning principles:

$$Kp = Kp0 + \Delta Kp \tag{2.2}$$
$$Ki = Ki0 + \Delta Ki \tag{2.3}$$
$$Kd = Kd0 + \Delta Kd \tag{2.4}$$

In the formulas (2.2), (2.3) and (2.4), Kp0, Ki0 and Kd0 are the initial preset values of PID parameters in the control system ΔKp, ΔKi and ΔKd are the self-regulating parameter values. Kp, Ki and Kd are the final output values after the fuzzy PID controller.

In order to meet the requirements of the stability and accuracy of the algorithm for the time-varying nonlinear system of the smart car, as well as the characteristics and debugging requirements of the smart car, the fuzzy PID controller adopts a two-input three-output mode [13]. In this mode, the input variables are error E and error change rate EC, and the output variables are Kp, Ki and Kd. In order to discretize the input variables, we divide the continuous interval [-1,1] into seven elements, and use the set of these seven elements as the domain of discourse, E, EC = { NB, NM, NS, ZO, PS, PM, PB }, and define the value range of fuzzy variables E and EC.

In the actual debugging, according to the experience, the error E and the error change rate EC are quantified into 7 grades, namely { -1, -0.7, -0.3,0,0.3,0.7,1}. On this basis, 49 fuzzy rules are established. The trigonometric function is used to represent the membership function of the output variable, and the Gaussian curve function is used to represent the membership function of the input variables E and EC [14]. The specific function form is shown in Figure 3.

Based on the comprehensive setting principle, the membership function curve of the input and output variables of the controller and the actual experience of the operation value of the intelligent vehicle, the fuzzy control rules of the output variables can be obtained, as shown in Table 2, 3, 4.

Table 2. Kp fuzzy control adjustment planning

Error E	Error change rate EC						
	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PM	PM	PS	PS	PS
NM	PM	PM	PM	PS	PS	PS	PS
NS	PS	PS	PS	ZO	ZO	ZO	ZO
ZO	ZO	ZO	ZO	ZO	ZO	ZO	ZO
PS	ZO	ZO	ZO	NS	NS	NM	NM
PM	NM	NS	NS	NM	NM	NM	NM
PB	NS	NS	NS	NM	NB	NB	NB

Table 3. Ki fuzzy control adjustment planning

Error E	Error change rate EC						
	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NM	NM	NS	ZO	ZO
NM	NB	NB	NM	NS	NS	ZO	ZO
NS	NB	NM	PS	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 4. Kd fuzzy control adjustment planning

Error E	Error change rate 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	ZO	ZO	PS	PM	PM	PB	PB

By constructing a fuzzy inference systemstructure file, the designed membership function and a fuzzy controller containing 49 fuzzy rules are embedded in the fuzzy logic control simulation module of MATLAB.We completed the construction of a fuzzy adaptive PID controller. In the controller, the Kp, Ki, Kd coefficients are output after the fuzzy controller is processed, and the corresponding surfaces are shown in Figure 4,5,6.

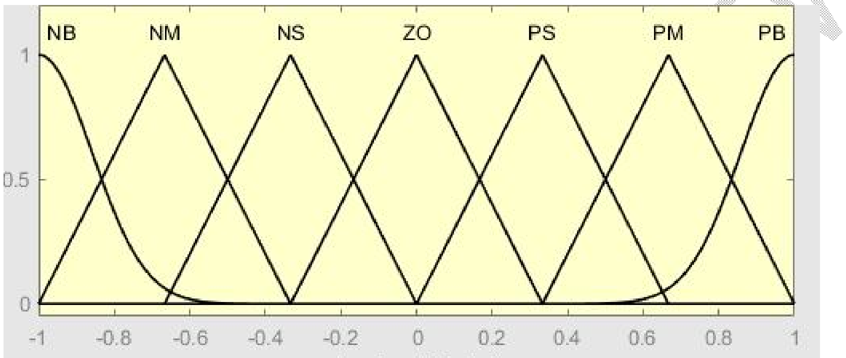

Fig.3.E and EC membership function curve

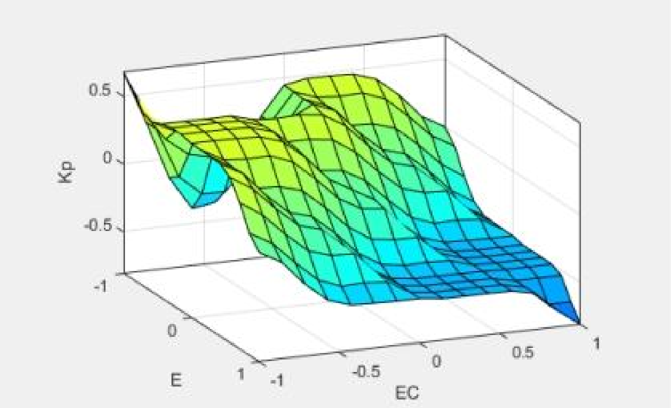

Fig.4. Fuzzy control Kp output surface

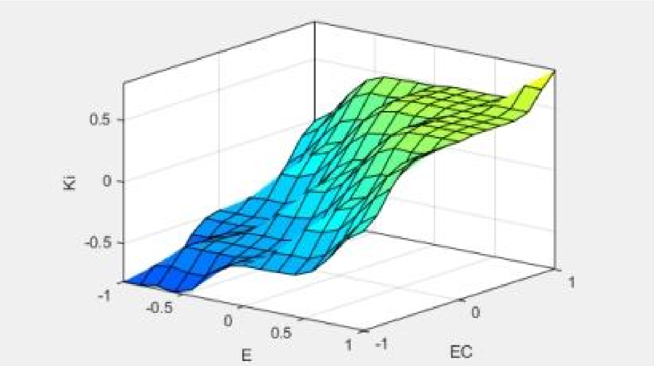

Fig.5. Fuzzy control Ki output surface

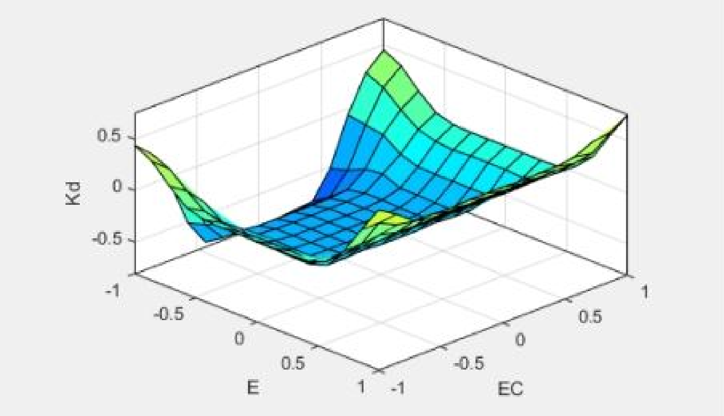

Fig.6. Fuzzy control Kd output surface

The significance of this surface is to guide the control output of the system, determine the corresponding control quantity through the fuzzy output value, and adjust the state of the controlled object. Specifically, the mapping relationship between the fuzzy output and the fuzzy control Kd output surface can be established. Once the fuzzy controller outputs a certain fuzzy quantity, it can be directly converted into the corresponding control output. This surface can be regarded as an important part of the fuzzy controller. Its role is to map the abstract fuzzy output value into a specific control output to achieve precise control of the controlled object.

3. RESULTS AND DISCUSSION

(1) Compared with the classical PID experiment

In order to highlight the superiority of adaptive fuzzy PID control, we compared the traditional PID control, combined with the mathematical model of the motor, the experiment was carried out on the Simulink simulation platform, as shown in Fig.7. The simulation data is further written into the intelligent vehicle for experiment. The optimal PID parameters are obtained by continuous debugging and experiment: P = 50, I = 0.8, D = 0.23. Under this parameter combination, the overshoot of the waveform diagram is the smallest and the stability time is the shortest.

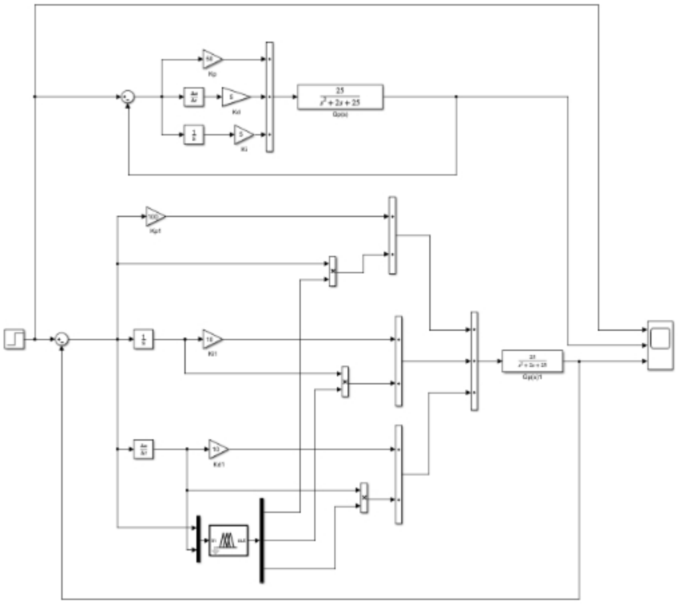

Fig.7. System block diagram of fuzzy PID controller

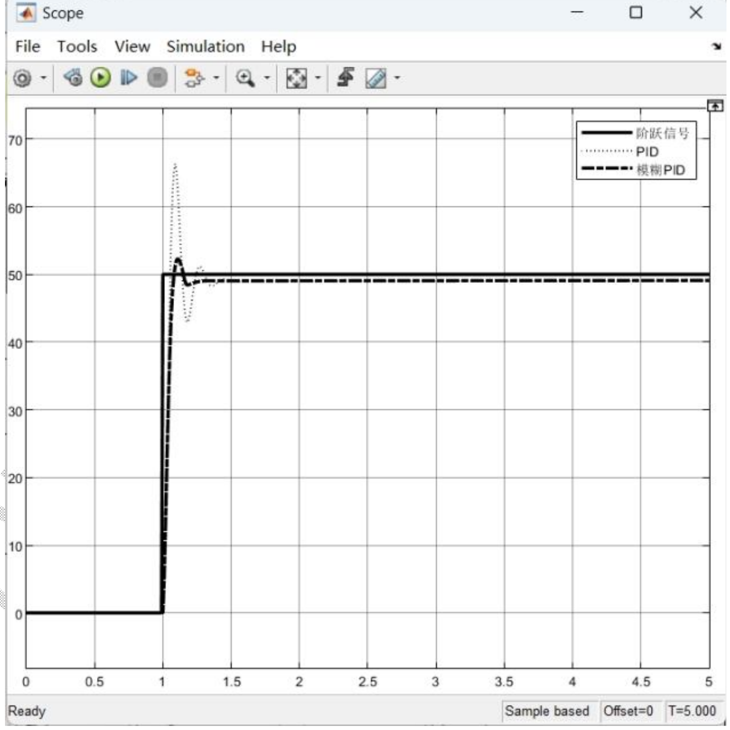

Fig.8. Adaptive fuzzy PID control response diagram

It can be seen from the simulation result Figure. 8 that compared with traditional PID control and incremental PID control, adaptive fuzzy PID control has better control effect and higher stability. Under different working environments and operating conditions, the adaptive fuzzy PID controller can automatically adjust the control parameters to achieve more accurate and stable control. In comparison with incremental PID control, the overshoot of adaptive fuzzy PID control is almost 0, indicating that adaptive fuzzy PID control greatly improves the rapid response and robustness of the control system. This also further proves the superiority and applicability of adaptive fuzzy PID control in automatic control systems.

(2) Anti-interference test of fuzzy PID control

In the stable state of the system, if a large speed or sharp deceleration is suddenly given, this instantaneous change will cause great interference to the control system and cause further instability of the system. However, with the support of adaptive fuzzy PID control, the system can adapt to different load and working conditions by automatically adjusting the control parameters, so as to achieve fast response and strong robustness.

For example, after giving the system a large speed signal, the control system Fig. 9shows that the gain is generated, but the system is quickly stabilized by the support of adaptive algorithm and fuzzy control, and there is almost no overshoot in the control response, showing strong control ability and reliability.

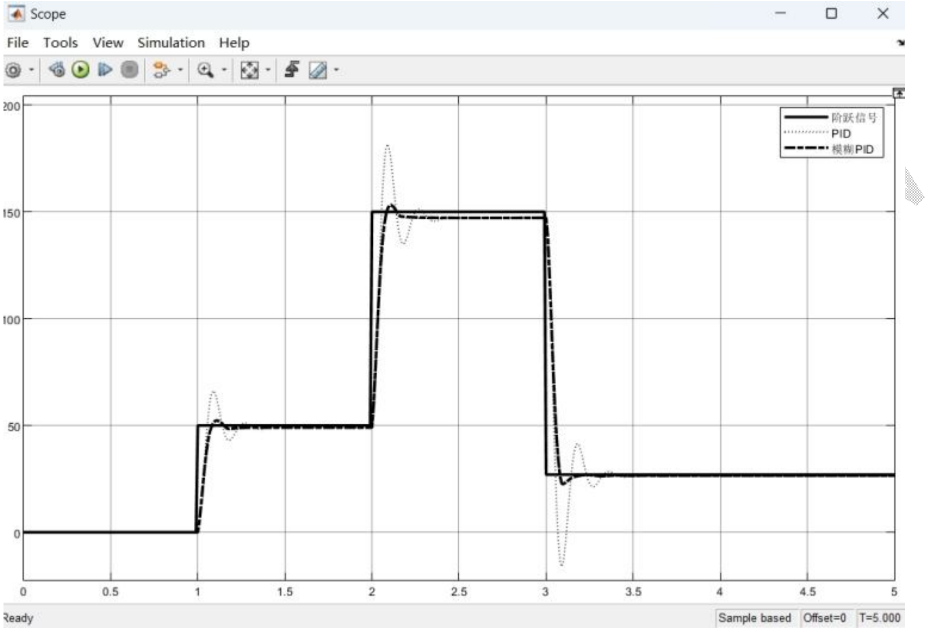

Fig.9. Adaptive fuzzy PID control response diagram

According to the simulation results of Fig.9, it can be concluded that the adaptive fuzzy PID control has a significant inhibitory effect on the system turbulence caused by the sudden increase of the speed. By adjusting the PID parameters in a timely and adaptive manner, the adaptive fuzzy PID controller can improve the stability and fast response of the control system, effectively deal with the emergencies and changes faced by the system, and achieve more accurate and reliable control. This also further verifies the superiority and applicability of adaptive fuzzy PID control in automatic control systems.

4. CONCLUSION

This paper introduces the traditional incremental PID control algorithm, and the simulation results show that the algorithm can control the operation of the intelligent vehicle more smoothly. At the same time, this paper also introduces the adaptive fuzzy PID control algorithm, and designs the fuzzy control rule table. Through MATLAB simulation experiments, the results show that compared with the traditional incremental PID control algorithm, the fuzzy control PID algorithm can greatly improve the overshoot and stability time. The conclusion of this paper shows that the fuzzy PID control algorithm is better than the traditional incremental PID control algorithm in the control of intelligent vehicle, which is beneficial to the practical application of intelligent vehicle.

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