Homeostasis of a Quadrotor UAV based on Fuzzy Adaptive PID controller

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Abstract. With the development of automatic control technology, quadcopter UAVs based on PID controllers are widely used in many fields such as exploration, aerial photography, monitoring patrols, etc. Due to the fact that the controlled object has a certain nonlinearity in complex environments, there exists the problem that the motion control is inefficient, and the error still occurs after stabilization. To address this problem, this paper designs fuzzy adaptive PID controller based on fuzzy control theory to improve the stability and accuracy of motion control of quadrotor UAV after disturbance. The dynamics model of a quadrotor UAV is established by Newton's second law and Euler's formula, and fuzzy theory is introduced on the basis of PID control. The affiliation function model is selected and fuzzy rules are formulated to control the inputs and outputs in a fuzzy manner. Then the simulation environment is set up in the Simulink module of MATLAB with the input of a step signal. The performance of fuzzy PID controller is compared with conventional PID from the step signal response curve. Finally, the results of the response curve show that the overshoot of the fuzzy adaptive PID controller is much lower than that of the traditional PID, meanwhile, the error rate is also lower, which confirms that the fuzzy PID controller is more superior to anti-interference and dynamic stability, and it has a higher control efficiency in the complex and changing environment.

Keywords: PID, Quadcopter UAV, Fuzzy Control

1 Introduction

As the rapid advancement of automatic control technology, the flight speed, stability, cruise time and other properties of UAVs are constantly improving, and they are widely used in aerial photography, exploration, monitoring and other fields. However, most of the quadcopter UAVs based on traditional PID controllers on the market nowadays have problems such as long adjustment speed and large stabilization error under the complex working environment of nonlinear systems, and there is still much room for improvement in control accuracy and efficiency.

Attitude stabilization system control improvement for quadrotor UAVs has been a research hotspot [1], in order to enhance the dynamic stability of motion control of UAVs in the environment subject to external disturbances and to reduce the error, Hai-Tao Zhang et al. designed a gravity compensated single neuron PID controller, after

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feedforward control to compensate gravity, the position loop is controlled by PID to ensure the control accuracy, and the attitude loop is controlled by single neuron to increase the adaptive capability [2]. Takaoglu, Faruk et al. proposed a reference-free inertial frame multi-rotor UAV model using adaptive genetic algorithm (AGA) to optimize the MS-PID controller to control the quadrotor UAV's flight attitude [3]. Compared with the traditional PID control, the controller of the above improved algorithm model greatly increases the anti-jamming property of the quadrotor UAV, but it still exists the problems of huge computation and complicated parameterization, which makes it difficult to be applied in engineering practice.

In order to efficiently improve the UAV's anti-interference and stability, as well as to solve the problem of low efficiency and accuracy of UAV motion control, this paper designs a fuzzy PID controller based on the fuzzy control theory and the dynamics model of the quadrotor UAV [4]. The static motion parameters of the UAV can be adjusted to improve the self-resistance and the robustness of the UAV control system in the complex environment.

2 Research Methodology

2.1 Coordinate System Selection and Transformation Relations

The quadrotor UAV has three linear and three angular motions with a total of six degrees of freedom of motion, so the quadrotor UAV has both translational and rotational motions in the direction of the X, Y, and Z axes, and the translational motion is represented by the displacements x, y, and z. The roll, pitch, and yaw motions are represented by the roll angle ϕ, the pitch angle θ, and the yaw angle ψ of the UAV. The inertial coordinate system is selected as the coordinate system of the quadrotor UAV's translation, at this time, the UAV's translation is not related to the rigid model of the body, so the UAV's motion can be regarded as the motion of the mass point, and the dynamics analysis model of the mass point is established for it. Take the center point of the quadcopter UAV as the coordinate center, establish the body coordinate system as the coordinate system of the quadcopter UAV rotation, at this time, the UAV is a rigid model, subject to the action of the force and torque, to do rigid motion.

After selecting the two coordinate systems of the quadcopter UAV, we need to make the following assumptions about the experimental environment in order to exclude the complex factors affecting this study, reduce the errors in the results, and make the results clearer and more accurate [5]. First, the ground coordinate system is an inertial coordinate system, the ground surface is regarded as a plane, and the gravitational acceleration does not change with height. Second, the effects caused by the rotation and revolution motion of the earth are ignored. Moreover, the quadrotor is only subject to gravity and propeller pull. Finally, the helicopter is a rigid body and its mass does not change with motion. The quadrotor unmanned helicopter has a good symmetry in its shape and structure and mass distribution, and the center of gravity is approximated to be located at the center of the airframe.

The transformation matrix R from the airframe coordinate system to the ground coordinate system is [6]:

$$\begin{pmatrix} cos\theta cos\psi & \sin\theta\cos\psi\sin\phi - \sin\psi\cos\phi & \sin\theta\cos\psi\cos\phi + \sin\psi\sin\phi \\ \cos\theta\sin\psi & \sin\theta\cos\psi\sin\phi + \cos\psi\cos\phi & \sin\theta\sin\psi\cos\phi - \cos\psi\cos\phi \\ -\sin\theta & \cos\theta\sin\phi & \cos\theta\cos\phi \end{pmatrix}$$

Here define $J = (x, y, z)^T$ as the position coordinates of the UAV in the inertial coordinate system, and define $\alpha = (\phi, \theta, \psi)^T$ as the attitude angle coordinates of the UAV in the airframe coordinate system.

2.2 Establishment of Dynamic Equations for Quadrotor UAVs

The quadrotor UAV is driven by four motors to generate lift and torque from the rotation of the rotors, ideally, the UAV is flown at low speeds with negligible air resistance, the UAV model is shown in the Figure 1, with the 1 and 3 propellers moving clockwise and the 2 and 4 propellers moving counterclockwise.

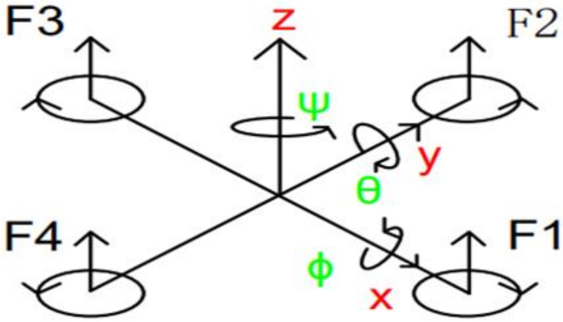

Fig. 1 Mechanical modeling of a quadrotor UAV

When the UAV makes a fixed-height motion, at this time, the four propellers generate lift simultaneously, and the combined external force on the UAV in the inertial coordinate system is the vector sum of the lift of the UAV and its own gravity.

When the drone is elevated, the sum of the lift forces generated by the rotors, F_0, is

$$F_0 = F_1 + F_2 + F_3 + F_4 \tag{1}$$

Where, F_1, F_2, F_3, F_4 are the lift generated by the four rotors.

When the UAV does a roll motion, the lift of propellers 1 and 3 remains constant, propellers 2 and 4 change the lift, and the roll moment τ_P is

$$\tau_P = l(F_4 - F_2) \tag{2}$$

where l is the wheelbase of the UAV.

When the drone makes a pitching motion, as opposed to a rolling motion, the pitching moment τ_q is

$$\tau_q = l(F_3 - F_1) \tag{3}$$

When the UAV makes a yaw motion around the Z-axis, the yaw moment at this point is

$$\tau_r = dl(F_4 - F_3 + F_2 - F_1) \tag{4}$$

where d is the torsion coefficient.

In order to design the controller, it is necessary to model and solve the inputs and inputs of the UAV, in which the four torques that will be generated by the quadrotor UAV when the motors rotate can control four inputs [7], which are the fixed-height motion control U_1, the roll motion control U_2, the pitch motion control U_3, and the yaw motion control U_4. Where neglecting air resistance, the lift of each rotor is proportional to the square of the rotational speed of its motor:

$$F_i = b\omega_i^2 \tag{5}$$

where b is the lift coefficient of the rotor, F is the lift generated by the propeller, ω is the rotational speed of the rotor, i = 1, 2, 3, 4.
Calculated from the above equation:

$$U_1 = b(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2) \tag{6}$$

$$U_2 = b(\omega_4^2 - \omega_2^2) \tag{7}$$

$$U_3 = b(\omega_3^2 - \omega_1^2) \tag{8}$$

$$U_4 = d(\omega_4^2 - \omega_3^2 + \omega_2^2 - \omega_1^2) \tag{9}$$

2.3 Solving for Transfer Functions

In order to build the subsequent controller, we solved the transfer function for the input and output functions of the UAV model.

By Euler's formula and Newton's second law and combining the above formulas to establish a nonlinear dynamics model of a quadrotor UAV [8], it can be deduced that

$$\ddot{x} = (\cos\psi \sin\theta \cos\phi + \sin\psi \sin\phi)U_1/m \tag{10}$$

$$\ddot{y} = (\sin\psi \sin\theta \cos\phi - \cos\psi \sin\phi)U_1/m \tag{11}$$

$$\ddot{z} = (\cos\theta \cos\phi)U_1/m \tag{12}$$

$$\ddot{\phi} = \left[lU_2 + \dot{\theta}\dot{\psi}(I_y - I_z)\right]/I_x \tag{13}$$

$$\ddot{\theta} = \left[lU_3 + \dot{\phi}\dot{\psi}(I_z - I_x)\right]/I_y \tag{14}$$

$$\ddot{\psi} = \left[lU_4 + \dot{\phi}\dot{\psi}(I_x - I_y)\right]/I_z \tag{15}$$

where l is the axis distance of the UAV, m is the mass of the UAV, and I_x, I_y and I_z are the moment of inertia of the X, Y, and Z axes, respectively. The relevant parameters of the quadcopter UAV are shown in the Table 1.

Table 1. Drone-related parameters

Parameters	Notation	Numerical value
Gravity acceleration (m/s²)	g	9.83
UAV mass (kg)	m	1.431
UAV wheelbase (m)	l	0.327
X-axis moment of inertia/(kg/m²)	I_x	0.0095
Y-axis moment of inertia/(kg/m²)	I_y	0.0095
Z-axis moment of inertia/(kg/m²)	I_z	0.0186
Lift factor/[(N-min2)/r2]	b	1.5185×10^{-7}
Torsion factor/[(N-m-min2)/r2]	d	2.825×10^{-9}

Define the quadrotor UAV as an underdriven system with inputs U_1, U_2, U_3, and U_4, and outputs are the body's fixed-height motion, pitch motion, roll motion, and yaw motion defined by z, θ, ϕ, and ψ. From the transfer function matrix $G\ (s) = \ (sI - \ A)^{-1}$ Band the state matrix A and control matrix B obtained from the state space equations, the following transfer functions can be obtained.

Fixed-height motion transfer function:

$$G_1 = \frac{2.834}{s^2+13.27s} \tag{16}$$

Yaw motion transfer function:

$$G_2 = \frac{108.7}{s^2+431.5s} \tag{17}$$

Roll motion transfer function:

$$G_3 = \frac{79.36S+8213}{s^3+127.8s^2+1658s+2774} \tag{18}$$

Pitch motion transfer function:

$$G_4 = \frac{79.36S+8213}{s^3+127.8s^2+1658s+2774} \tag{19}$$

where G denotes the transfer function and s is the Laplace transform of the complex variable.

2.4 Controller Construction

PID controller. The mathematical model of the conventional PID controller is [9]:

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \tag{20}$$

Where, $u(t)$ is the output signal of the PID control system, e is the amount of system error, K_p, K_i, K_d are the proportional, integral, and differential coefficients of the system. in the PID controller, the proportional control P carries out the basic control of the system, the integral control I is the correction of the error, and the differential control D increases the system's broadband and shortens the response time.

Fuzzy Adaptive PID Controller. Since the traditional PID cannot be changed after setting the parameters, for the variable and complex environment and the dynamic characteristics of the UAV, based on the fuzzy theory, the fuzzy control is added on the basis of its PID controller. The fuzzy processor is constructed through the affiliation function model and thesis domain established by the expert experience, and at the same time, the quantization factor and the proportionality factor are added as the correction coefficients in its input and output, and finally the error $\boldsymbol{e}$ and the error change rate $\boldsymbol{ec}$ can be obtained as the dynamically varying parameters $\boldsymbol{\Delta K_p}$, $\boldsymbol{\Delta K_i}$, and $\boldsymbol{\Delta K_d}$ after passing through the fuzzy processor, which are added with the PID parameters $\boldsymbol{K_p}$, $\boldsymbol{K_i}$, and $\boldsymbol{K_d}$ and finally can be obtained as The dynamically changing $\boldsymbol{K_p}$, $\boldsymbol{K_i}$, $\boldsymbol{K_d}$. This dynamically changing fuzzy controller can continuously regulate and optimize the control effect of the controller [10].

3 Results of the Study

Based on MATLAB's Simulink module to build a virtual simulation environment, the experiment initially selected the transfer function of the second-order system in the quadcopter UAV fixed height motion, and thus design the traditional PID controller. By adjusting the parameters of the PID controller, the values of K_p, K_i, and K_d are obtained as 40, 1, and 0.5 respectively, and the step signal is input to the system, and the step signal response curve is finally obtained. The simulation environment and results are shown in the Figure 2 and Figure 3, respectively.

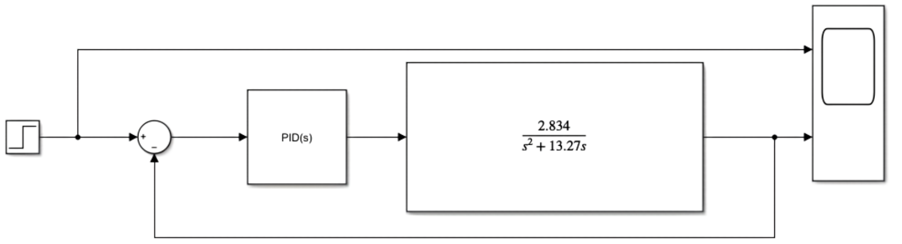

Fig. 2 Fixed height motion PID controller

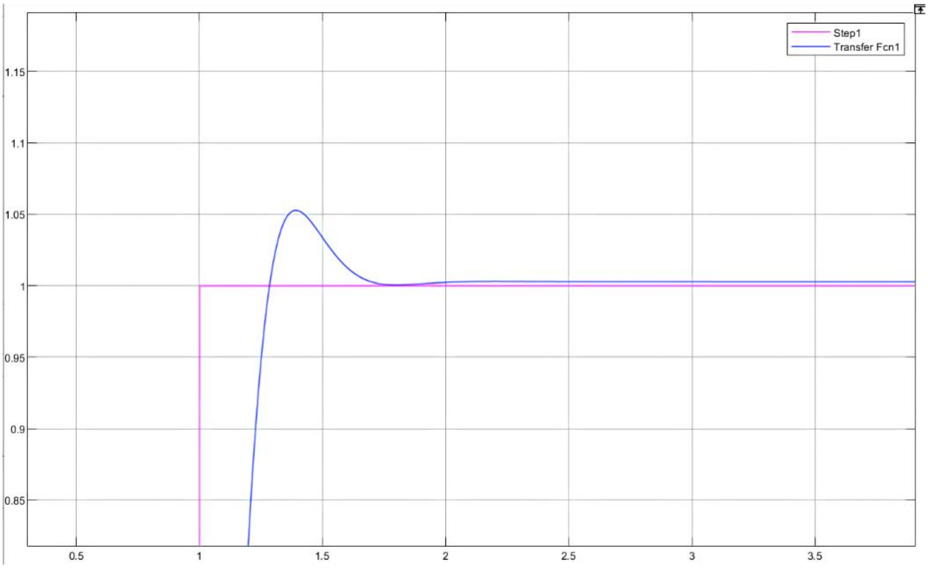

Fig. 3. Response curve of fixed-height motion PID controller subjected to a step signal

In order to make a fuzzy adaptive PID controller, we first have to make a fuzzy processor. Here the experiment is done using the fuzzy processor module of Simulink and Mamdani fuzzy inference algorithm is used. For this system, the fuzzy domain is chosen as (-1,1) and also the triangular affiliation function is chosen and a total of 49 fuzzy rules are defined. The system error e and the rate of change of the error ec are used as inputs for the fuzzification operation. Firstly, they are transformed by the quantization factor, and then through the zero-order keeper and the fuzzy controller, the dynamically varying quantities ΔK_p, ΔK_i, and ΔK_d are output through the amplification effect of the proportionality factor, and they are summed up with the conventional PID parameters K_p, K_i,, and K_d to obtain the final output dynamically varying fuzzy PID parameters $fuzzy\_Kp$, $fuzzy\_Ki$, and $fuzzy\_Kd$ [11]. The fuzzy processor fabrication process and the final fuzzy PID controller is shown in the Figure 4 and Figure 5 respectively.

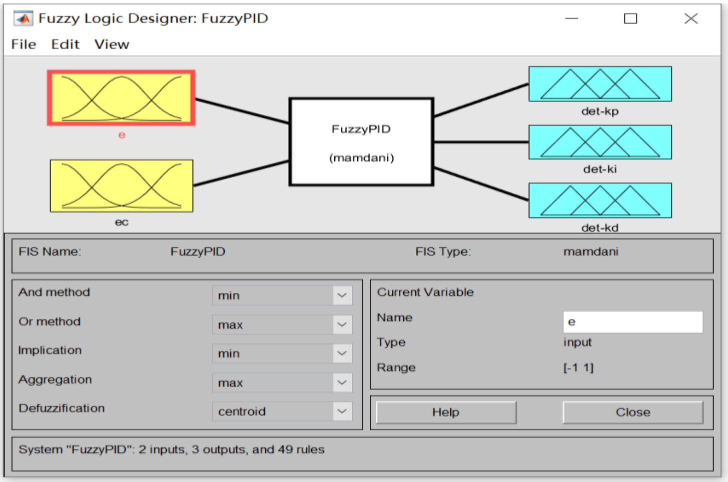

Fig. 4. Fuzzy processors and the setup of the thesis domain

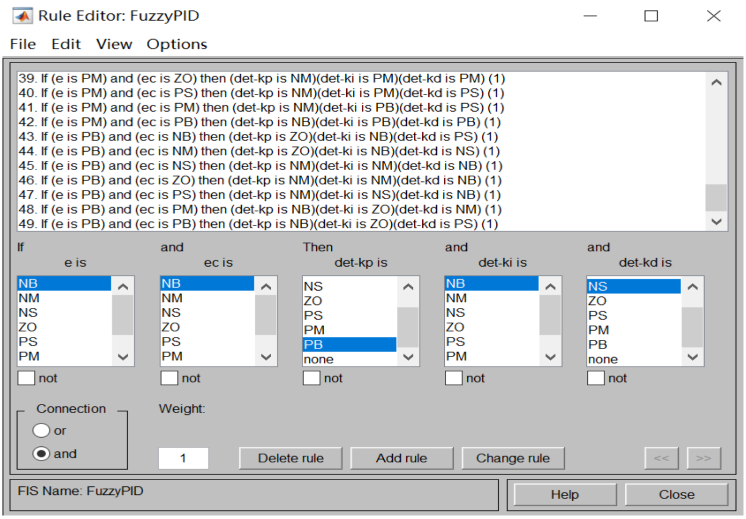

Fig. 5. Fuzzy rulemaking

Finally, the experiment inputs a step signal to the fuzzy adaptive PID controller, obtains the step signal response curve, and compares it with the response curve of the traditional PID, and the results are shown in the Figure 6 and Figure 7, respectively.

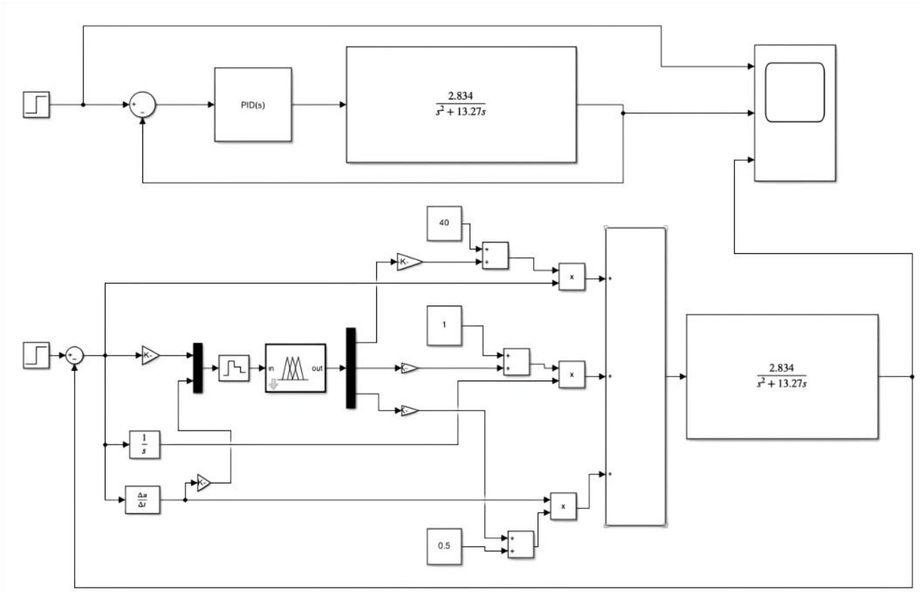

Fig. 6. Fuzzy Adaptive PID Controller

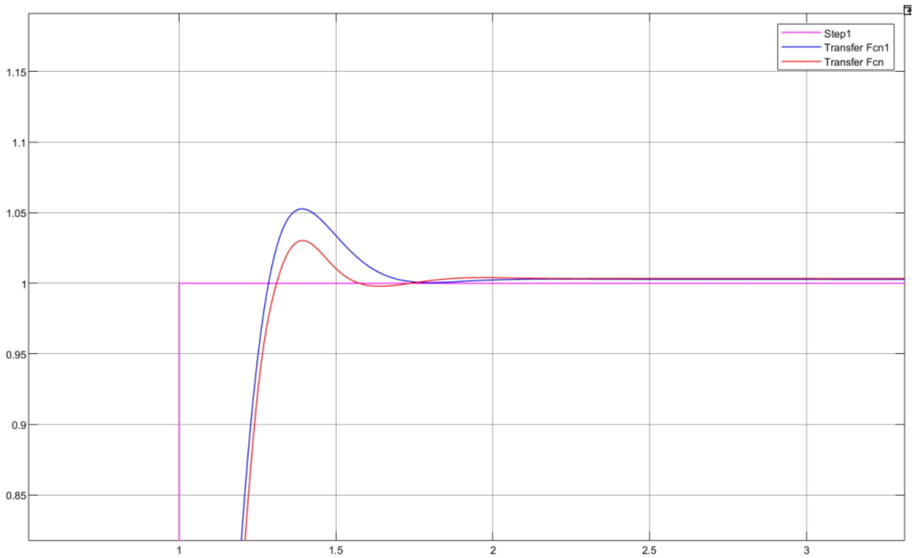

Fig. 7. Response curves of two controllers for fixed-height motion under a step signal

In order to further verify whether the fuzzy adaptive PID controller has better superiority over the traditional PID controller, a set of PID and fuzzy PID controllers based on the third-order system transfer function of the rolling motion is added to the experiment. The third-order system transfer function of the tumbling motion has a higher system order than the second-order transfer function of the fixed-height motion, which means that the system will be more complex and less controllable. According to the above experimental procedure the conventional PID controller for tumbling motion is also fabricated and its response curve obtained under the input of step signal is tested and the results are shown in the Figure 8 and Figure 9, respectively.

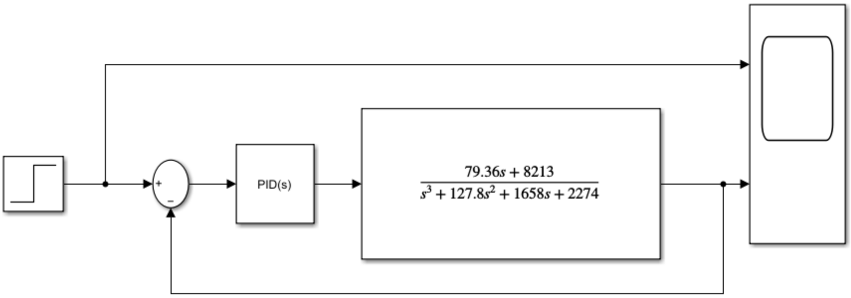

Fig. 8. Roll motion PID controller

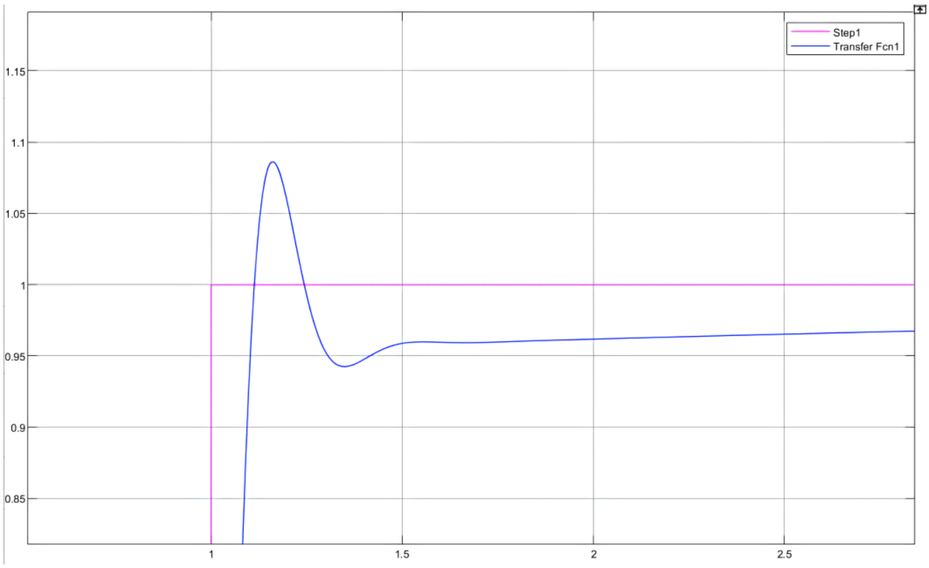

Fig. 9. Response curve of Roll motion PID controller subjected to a step signal (Photo credited: Original)

Similar to the design of fuzzy adaptive PID controller for fixed height motion, the same fuzzy control is added to the PID controller for roll motion and a fuzzy processor is designed and the results obtained are shown in the Figure 10 and Figure 11, respectively.

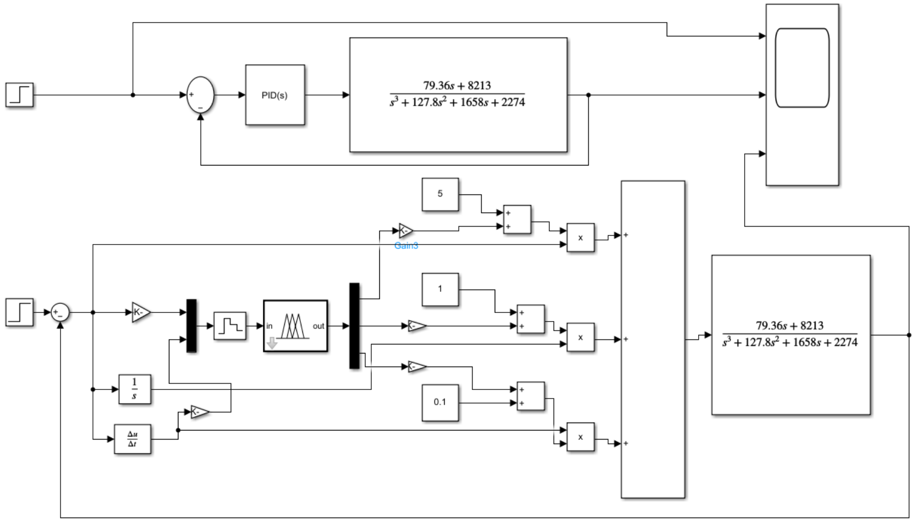

Fig. 10. Fuzzy Adaptive PID Controller for Rolling Motion

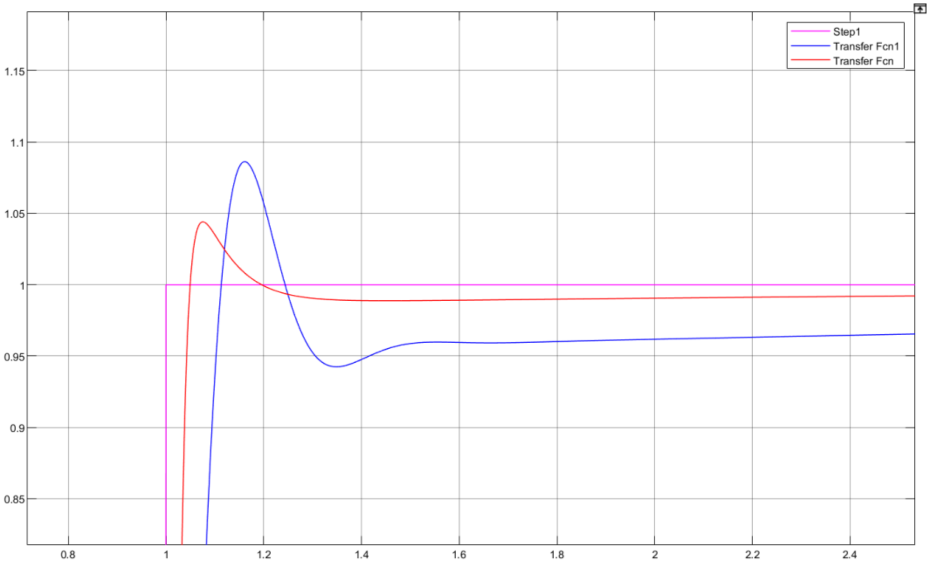

Fig. 11. Response curves of two controllers for roll motion under a step signal

4 Analysis of Experimental Results

In order to make an effective comparison between the performance of the conventional PID controller and the fuzzy PID controller, three data from automatic control theory, the overshooting amount σ_p, the steady-state regulation time t_s, and the steady-state error e_{ss} will be used as the basis for the comparison. The formulas are calculated as follows:

$$\sigma_p = \frac{Y_{max} - Y_S}{Y_S} \times 100\% \tag{21}$$

where Y_{max} denotes the peak value of the system response curve and Y_s denotes the steady state value of the system response curve.

$$e_{ss} = Y_s - Y_e \tag{22}$$

where Y_e is the expected value of the system response curve after steady state.

As a result, experiments were conducted to obtain comparative data between the conventional PID controller and the fuzzy PID controller for fixed-height motion, and the results are as follows (see Table 2):

Table 2. Performance Comparison of Two Controllers for Constant Height Motion

Data type	Conventional PID controller	Fuzzy PID controller
Overshoot（σ_p）	5.11%	3.02%
Steady-state regulation time（t_s）	1.08s	0.87s
steady-state error (e_{ss})	0.003	0.0028

From Table 2, it can be learned that based on the traditional PID controller, fuzzy PID has lower overshoot, faster steady state regulation time and smaller steady state error when controlling the fixed height motion of the UAV.

Next a comparison is made between the conventional PID controller and the fuzzy PID controller obtained for the third-order system transfer function of the rolling motion, and again the performance is measured in terms of the amount of overshooting σ_p, the steady-state regulation time t_s, and steady-state error e_{ss}. The data are as follows (see Table 3)：

Table 3. Performance Comparison of Two Controllers for Rolling Motion

Data type	Conventional PID controller	Fuzzy PID controller
Overshoot（σ_p）	8.32%	4.38%
Steady-state regulation time（t_s）	0.52s	0.33s
steady-state error (e_{ss})	0.0453	0.0174

The data in Table 3 shows that the fuzzy adaptive PID controller for roll motion still has better performance indicators compared to the conventional PID controller. Through the third-order system transfer function and the transfer function of the second-order system derived from the comparison of data, for higher-order as well as more complex environments, more difficult to control the conditions, the superiority of fuzzy adaptive PID controllers compared to traditional PID controllers has a significant increase in the effect of the superiority of the effect. Therefore, we can conclude that the fuzzy adaptive PID controller is more stable in the control of the UAV, and the control accuracy is also more accurate, which increases the stability and anti-interference of the UAV control, and greatly improves the control efficiency.

5 Conclusion

In the process of UAV control, the overshooting amount, steady state regulation time and steady state error of the UAV will affect the control accuracy and system stability of the UAV, especially in the complex nonlinear environment. In the comparison experiment between fuzzy adaptive PID control and traditional PID control, by inputting the step signal to simulate the dynamic environment and conducting comparison analysis, it can be concluded that all the performances of fuzzy PID control are better than traditional PID control. Especially when the transfer function system order of the controlled system is increased, under more complex control difficulty, the fuzzy adaptive PID control has a more significant superiority compared to the traditional PID control, which indicates that the UAV with fuzzy PID controller has stronger anti-interference and stability, and also has a more powerful working potential. Therefore, the fuzzy adaptive PID controller has good development and application prospects in the steady state control of UAV.

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