Ant colony algorithm based fuzzy PID control of unmanned aerial vehicle under wind disturbance conditions

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Abstract:

A drone is an unmanned aerial vehicle that has been widely used in military, civil and commercial fields. UAVs need to maintain a smooth and stable flight state during flight to accomplish various tasks, such as reconnaissance, scouting, aerial photography, transportation, and so on. In this paper, both the ant colony algorithm and fuzzy PID control are utilized to investigate the control of quadrotor UAVs under wind disturbance conditions. The optimization of the fuzzy PID control algorithm is conducted through the application of a convolutional neural network under wind disturbance conditions.The system construction and simulation test are conducted using MATLAB and Simulink. The experimental results are analyzed, experimental conclusions are drawn, and the results are compared with those obtained using the traditional PID control algorithm and fuzzy PID control algorithm. This comparison helps demonstrate the extent of optimization achieved by the convolutional neural network on the fuzzy PID control algorithm.The results obtained from comparing the performance with the traditional PID control algorithm and fuzzy PID control algorithm demonstrate the degree of optimization achieved by applying the convolutional neural network to the fuzzy PID control algorithm. The findings indicate that the fuzzy PID control, optimized by the ant colony algorithm, can effectively be utilized for controlling quadrotor UAVs under wind disturbance conditions.

Keywords: Ant colony algorithm, wind disturbance, fuzzy PID control, unmanned aerial vehicle

1. Significance of the research topic and overview of its current status worldwide

A drone is an unmanned aerial vehicle that has been widely used in military, civil and commercial fields. UAVs need to maintain a smooth and stable flight state during flight in order to accomplish a variety of tasks, such as reconnaissance, scouting, aerial photography and transportation.

To ensure a stable flight state for UAVs during their operations, it is essential to employ a stable and mature control method. The main UAV control methods commonly used at present are:

1. Model Predictive Control (MPC): MPC is an optimization algorithm that utilizes a dynamic model of the system to predict its future behavior. By optimizing the control inputs over a future time horizon, MPC aims to achieve a balance between performance objectives and system constraints. MPC is known for its high accuracy and adaptability in UAV control.

2. Advanced control methods, such as nonlinear control, adaptive control, and robust control, are capable of effectively addressing the challenges posed by nonlinearities, time-varying dynamics, and uncertainties in complex environments for quadrotor UAVs. These methods aim to enhance control accuracy and robustness.

3. Deep learning control: Deep learning control is a control method that leverages deep learning algorithms to enable autonomous control of quadrotor UAVs through extensive data learning and training. This approach allows the UAV to autonomously navigate, handle obstacle avoidance, and excel in other aspects with high levels of intelligence and adaptability.

4. Optimal Control: Optimal control algorithms aim to minimize a specified performance metric, such as energy consumption or time, by optimizing the control inputs to achieve the best possible system performance. These algorithms are designed to find the control signals that optimize the system's behavior and achieve the desired objectives.

To address the limitations of the aforementioned control methods, fuzzy PID control is introduced in UAV flight control. Fuzzy PID control combines the concepts of fuzzy logic and the traditional PID control to handle uncertainty and ambiguity within the control system. Fuzzy PID control can also adaptively adjust the controller's parameters based on different environments and mission requirements, allowing it to adapt to various operating scenarios. Moreover, fuzzy PID control improves control accuracy and response speed by optimizing the input-output mapping function of the fuzzy controller.

The main focus of this paper is the system optimization of the fuzzy PID control algorithm using a convolutional neural network (CNN) under wind disturbance conditions. The research methodology involves building the system and conducting simulation tests using Matlab and Simulink. The experimental results are analyzed, and conclusions are drawn based on the findings. A comparison is made between the results obtained from the traditional PID control algorithm, the fuzzy PID control algorithm, and the proposed CNN-based fuzzy PID control algorithm. The objective is to demonstrate the effectiveness of the convolutional neural network in enhancing the performance of the fuzzy PID control algorithm.

2. Wind disturbance model analysis and modeling

2.1 introductory

This chapter focuses on the simulink simulation wind disturbance model used in the selected topic. The principle is analyzed and different types of wind are classified and integrated and the resultant graphs of the simulation model are given.

2.2 Principle analysis of wind disturbance model

In contrast to the controlled laboratory training environment, quadrotor UAVs face complex disturbances from various sources in natural settings. Among these disturbances, wind disturbances are prevalent and have a significant impact on quadrotor UAVs.Since the flight stability of a quadrotor UAV depends on the cooperative work of the four rotors.Consequently, even slight wind disturbances may have a substantial impact on it, potentially causing the quadrotor UAV to wobble. As wind speed increases, the air resistance experienced by a quadrotor UAV intensifies, thereby limiting its flight speed. Simultaneously, wind disturbances alter the aerodynamic effects, leading to a decrease in the flight altitude of the quadrotor UAV. Moreover, wind disturbances can affect the flight direction, causing deviations from the original trajectory.

Wind is a form of motion in the atmosphere and is a manifestation of factors such as temperature, air pressure, and topography on the earth's surface. The characteristics of wind include wind direction, wind speed and wind force, which significantly impact human life and the natural environment. Wind exhibits characteristics of continuity, suddenness, gradual change and randomness. According to the characteristics, natural wind can be divided into four types: basic wind, gust wind, gradual wind and random wind.

Basic Wind: The basic wind refers to the average wind speed and direction observed over a specific duration, typically around 10 minutes. It is widely utilized in weather forecasting and meteorological observations to represent the prevailing wind conditions in a given area. The basic wind value, denoted as Va, is often considered constant for simplicity, representing the general wind characteristics of the area.

$$V_a = A$$

A gust wind is a sudden increase in wind speed over a short period of time that lasts for some time and then decreases. Gusts are usually caused by strong localized pressure gradients or topographical factors, and their duration usually ranges from a few seconds to a few minutes. The wind speed of gust has a cosine characteristic during its duration, as shown in the following equation:

$$V_{wg} = \begin{cases} 0 & t < t_{1g} \\ \frac{G_{max}}{2}[1 - \cos 2\pi \frac{t - t_{1g}}{t_g}] & t_{1g} < t < t_{1g} + t_g \\ 0 & t > t_{1g} + t_g \end{cases}$$

Where G_{max} is the peak gust, t_{1g} is the time of the start of the gust, and t_g is the gust period.

Gradual winds are wind variations characterized by changes in wind speed and direction influenced by factors like terrain, oceans, or buildings. Unlike gust winds, gradual winds exhibit a more continuous and gradual spatial trend, lacking sudden bursts or gusts. The velocity model for gradual winds can be described by the following equation:

$$V_{wr} = \begin{cases} 0 & t < T_{1r} \\ R_{max} \frac{t - T_{1r}}{T_{2r} - T_{1r}} & T_{1r} < t < T_{2r} \\ R_{max} & T_{2r} < t < T_{2r} + T_r \\ 0 & t > T_{2r} + T_r \end{cases}$$

Where R_{max} is the peak value of the gradual wind, T_{1r} is the start time of the gradual wind, T_{2r} is the end time of the gradual wind and T_r is the duration of the gradual wind.

Random wind, also known as noise wind speed, refers to the fact that due to the complex non-linear characteristics of the meteorological system, the wind speed and direction show random variations in time and space and are still characterized by continuity. The velocity profile of noise wind speed is shown in the following equation:

$$V_{wn} = V_{wn\max} R_{an}(-1,1)\cos(\omega_{wn}t + \varphi_n)$$

Where $V_{wn\ max}$ is the random wind peak, R_{an} (-1,1) is a random number uniformly distributed between -1 and 1, ω_{wn} is the average distance of wind speed fluctuations, and φ_n is a random quantity uniformly distributed between 0 and 2π.

In summary, the wind disturbance is a collection of the above four wind speed disturbance models. However, the impacts and duration of different wind speed systems are not the same, so it is necessary to weight the above four models and sum them up to get a complete wind speed disturbance model, with different weights to express the impact size. Different weights are used to express the impact size. Expressions for wind speed changes under various wind conditions can be listed for different weighting ratios:

$$V = aV_a + bV_{wg} + cV_{wr} + dV_{wn}$$

Where V_a , V_{wg} , V_{wr} , V_{wn} represent the four wind disturbance velocity types mentioned above; a, b, c, and d denote the proportion of weight that each wind type contributes to the whole, and the algebraic sum of a, b, c, and d is one.

The equation for the wind disturbing force can be derived from the overall wind speed obtained from the above equation as well as the momentum theorem:

$$F_t = mV$$

Where F_t denotes the wind disturbance force, m is the mass of the disturbed wind, V is the overall wind speed, and t is the disturbance duration.

Since the wind will form a force surface S on the surface of the UAV when the wind is perturbing the quadrotor UAV, the mass of the perturbing wind during the perturbation time can be expressed by the following equation:

$$m = \rho * S * V * t$$

From the above equation, the wind disturbing force F can be shown in the following expression:

$$F = \rho * S * V^2$$

where ρ is the air density.

From Eq. It is easy to see that the wind disturbance force is affected by three aspects: air density, disturbance force action area and overall wind speed. In the working process of the quadrotor UAV, because the UAV has a short endurance time, it usually does not produce a wide working range, and the air density does not change significantly; and the body structure of the UAV usually does not change significantly during the flight, so the air density ρ and the area of action S in the wind disturbing power formula can be regarded as two constants. In summary, the size of wind disturbance power is only related to the size of wind speed in general, and the expression of wind disturbance power can be rewritten as:

$$F = kV^2$$

where the constant k is the product of the air density ρ and the area of action S.

Therefore, the effect of wind disturbance power varies with the overall wind speed, the larger the overall wind speed, the larger the disturbance effect on the quadrotor UAV, and vice versa. Therefore the overall wind speed change model can be regarded as the model of wind disturbance force.

3. UAV dynamics model analysis and modeling

3.1 Principle analysis of quadrotor UAV model and establishment of mathematical equations

The principle of flight of a quadrotor drone is based on Newton's third law: for every action force there is a reaction force that is equal and opposite in direction.

A quadrotor drone consists of four rotating propellers and a battery. Each propeller generates thrust in a direction perpendicular to the plane of its rotation, which allows the combined force of the four propellers to control the motion of the vehicle. When the four propellers rotate at equal speeds, the vehicle can hover in the air. When forward movement is required, the flight controller increases the rotational speed of the back two propellers and decreases the rotational speed of the front two propellers, tilting the craft forward and accelerating it. Similarly, when it is necessary to move to the left or right, the controller increases the RPM of the propellers in the corresponding direction and decreases the RPM of the propellers in the opposite direction, causing the vehicle to tilt to the left or right and accelerate. The flight controller can also perform operations such as rotating, ascending or descending by adjusting the rotational speed of the propellers, thereby realizing various flight movements of the quadrotor UAV.

According to the above theory and the understanding of the UAV structure to get the quadrotor UAV aircraft schematic diagram shown in the figure below:

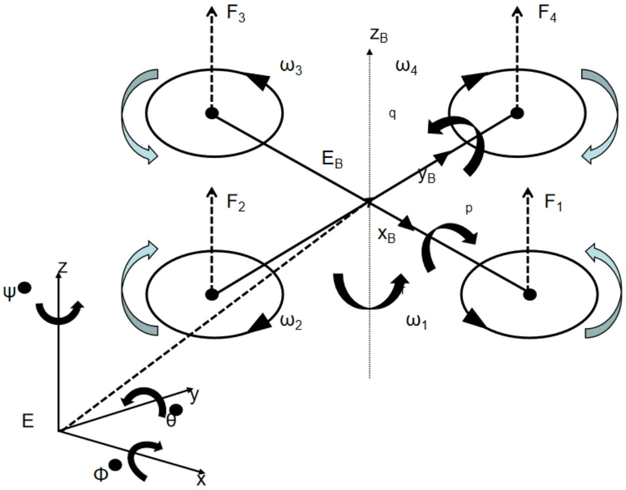

Figure 2.1 Flight schematic of a quadrotor UAV

As shown in the figure above, the power generated by the four rotors of the quadrotor UAV is F_1 , F_2 , F_3 , F_4 . The geocentric coordinate system (x-axis and y-axis are on the horizontal plane, and the z-axis is vertically upward) is translated to the takeoff origin of the UAV during the UAV's translation to avoid the interference of the Earth's center on the coordinate system parameters. When the UAV is rotating, the origin of the reference coordinate system is at the center of the fuselage, the x-axis is one arm of the UAV, the y-axis is the other arm perpendicular to it, the z-axis is perpendicular to the fuselage upwards, and the z-axis is the axis of rotation of the UAV at the same time.

There are three types of rotation in a quadrotor UAV: roll, pitch, and yaw. The angles during rotation are represented by Euler angles, which are categorized as follows: roll angle Φ for rotation around the x-axis, pitch angle θ for rotation around the y-axis, and yaw angle ψ for rotation around the z-axis.The angular velocities corresponding to each of the three Euler angles are denoted by the letters p, q, and r. The choice of the positive direction varies among the different Euler angles, where the angle is positive when rolling to the right, and the angle is positive when pitching. Different Euler angles are defined with positive directions for specific rotations. In this convention, the roll angle is considered positive when the rotation is towards the right, the pitch angle is positive when the rotation is upward, and the yaw angle is positive when the rotation is towards the right.

The position of the UAV can be solved by double integration of the acceleration, which can be obtained by Newton's second law.

If the drone hovers, we have $F_1 = F_2 = F_3 = F_4 = G/4 = mg/4$. At this point $a_x = a_y = a_z = 0$.

If the UAV is ready to take off, then $a_x = a_y = 0, a_z = -g + F_t/m$,where $F_t = F_1 + F_2 + F_3 + F_4$.

According to the Earth's coordinate system, the acceleration equation of the UAV during landing is the same as during takeoff.

The expression for the relationship between acceleration and force in each axis during linear motion of the UAV is given below:

$$\begin{cases} ma_x = F_t(\cos\Phi\sin\theta\cos\psi + \sin\Phi\sin\psi) \\ ma_y = F_t(\cos\Phi\sin\theta\sin\psi - \cos\psi\sin\Phi) \\ ma_z = -mg + F_t\cos\Phi\cos\theta \end{cases}$$

where $F_t = F_1 + F_2 + F + F_{34}$.

And the relationship between the moments during the rotational motion of the UAV is as follows:

Rolling moment: $\tau_p = -F_2 * l + F_4 * l$;

Pitching moment: $\tau_q = -F_1 * l + F_3 * l$;

Yaw moment: $\tau_r = -F_1 * d + F_2 * d - F_3 * d + F_4 * d$;

where the value of the force arm d needs to be obtained experimentally by testing with a torque transducer.

From the above equation, we can find the relationship equation of the corresponding angular velocity of each axis in the non-hovering state:

$$\begin{cases} I_x p' = (I_y - I_z)qr + \tau_p \\ I_y q' = (I_z - I_x)pr + \tau_q \\ I_z r' = (I_x - I_y)pq + \tau_r \end{cases}$$

Corresponding to the relational equation for each Euler angle:

$$\begin{cases} \Phi' = p + (r\cos\Phi + q\sin\Phi)\tan\theta \\ \theta' = q\cos\Phi - r\sin\Phi \\ \psi' = (r\cos\Phi + q\sin\Phi)/\cos\theta \end{cases}$$

In summary, the kinematic modeling of the quadrotor UAV revolves around both linear and rotational aspects, and the relationship between position, velocity, acceleration and force in the two states is derived by combining the geocentric reference system with the body reference system.

4. Design of PID controller

4.1 Classical PID control

PID control is a common feedback control method that derives its name from three control parameters: the proportional, integral, and differential terms, which correspond to the ratio, integral, and differential of the controller output to the error signal. In quadrotor UAVs, PID control is a common control method used to regulate the attitude (i.e., the angle of the vehicle) and altitude of UAVs, aiming to achieve stable and smooth flight.

The principle of PID control is based on the idea of feedback control, where the attitude or altitude of the vehicle is adjusted continuously to be as close as possible to the target value by constantly adjusting the controller output. The basic idea is that at each time step, an error signal is calculated and the controller output is computed based on the weights of the proportional, integral and differential terms. These weights usually need to be manually adjusted to achieve optimal control in different environments and application scenarios.

To implement PID control for a quadrotor UAV, it is typically achieved through cascaded loops or serial nesting. Attitude control of a quadrotor UAV usually uses three PID controllers corresponding to the pitch, roll and yaw angles. Each controller receives the error signal between the target angle and the actual angle and computes the controller outputs to adjust the rotational speeds of the four motors to control the attitude of the vehicle. The proportional term controls the magnitude of the error signal, the integral term controls the accumulation of the error signal, and the differential term controls the rate of change of the error signal.

4.2 Fuzzy PID control

The fuzzy PID controller consists of a classical PID controller and a fuzzy controller. The main principle of the fuzzy PID controller is to map the control error, the rate of change of the error, and the integral value of the error into three fuzzy sets, respectively, and then generate fuzzy control quantities by means of a fuzzy rule base. A fuzzy rule base is a set of IF-THEN rules derived from expert knowledge or experience, which describes the relationship between input variables and output variables. For example, "If the error is large and the rate of change of the error is large, the control volume is large", which is a fuzzy rule.

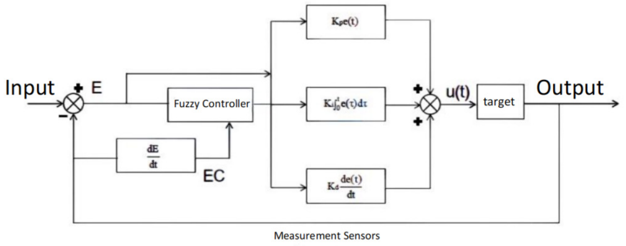

Fig. 4.1 Block diagram of fuzzy PID control system

From Fig. 4.1, the fuzzy controller consists of deviation E and deviation rate EC as inputs and ΔK_p, ΔK_i, ΔK_d as outputs. To ensure superior control performance of the fuzzy controller, it is essential to define more detailed fuzzy rules within the desired range of operation. This allows for a more comprehensive and precise mapping of input-output relationships, optimizing the control effect of the fuzzy controller. In the simulation process, the first step is the fuzzification of the input and output data, i.e., the exact data are divided into different sets according to the fuzzy theory domain. The fuzzy domain range of deviation E is set as [-3,3], the fuzzy domain range of deviation rate EC is [-1.5,1.5], the fuzzy domain ranges of ΔK_p, ΔK_i, and ΔK_d are set as [0,2], [-0.03,0.03], [0,5], and the fuzzy subsets are set as {NB,NM,NS,ZO,PS,PM,PB}.

5 ACO algorithm

5.1 introductory

Ant colony algorithm is a heuristic optimization algorithm based on the behavior of ant colony, which can be used to solve various optimization problems. In quadrotor UAVs, the ant colony algorithm can be used to optimize flight paths, control flight stability and other aspects.

The principle of the ant colony algorithm is to simulate the behavior of ants when searching for food. Ants leave pheromones in the environment when searching for food, and other ants can find food by sensing this pheromone.

The ant colony algorithm can be used to optimize the parameters of the fuzzy PID controller so that it can be better adapted to the control needs of a quadrotor UAV. For example, the parameters of the fuzzy PID controller can be regarded as one kind of solution in the solution space, and the control effect of the quadrotor UAV can be taken as the objective function, and then the ant colony algorithm can be used to search for the optimal solution. During the searching process, the ants can choose the next solution according to the adaptability of the current solution and their own experience, and after many iterations, the optimal controller parameters are finally obtained, thus realizing a better control effect.

5.2 PlatEMO Toolbox

5.2.1 Basic Introduction

PlatEMO is a MATLAB-based, open-source and free multi-objective optimization tool that can run in any operating system that supports MATLAB. It provides users with two running modes: command mode and GUI mode. In command mode, the GUI is not displayed and the user sets parameters and executes algorithms using commands; in GUI mode, the GUI is displayed and the user sets parameters and executes algorithms on the GUI. However, the MATLAB version requirement cannot be lower than R2020b (using the PlatEMO GUI).

5.2.2 Introduction to Use

In MATLAB, the user can run the main function 'platemo.m' file in the following three ways:

① Calling the main function with parameters:

platemo('problem',@SOP_F1,'algorithm',@GA);

Specified algorithms can be used to solve specified test problems and set parameters, and the results can be displayed in a window, saved in a file, or returned as a function.

② Calling the main function with parameters:

f1 = @(x)sum(x);

g1 = @(x)1-sum(x);

platemo('objFcn',f1,'conFcn',g1,'algorithm',@GA);

Customized problems can be solved using specified algorithms.

③ Calling the main function without parameters:

platemo();

A graphical interface with three modules can be popped up, where the test module is used to visualize the performance of a single algorithm on a single problem, the application module is used to solve custom problems, and the experiment module is used to statistically analyze the performance of multiple algorithms on multiple problems. In addition, PlatEMO can be used directly from the command line as well as from the graphical interface.

5.3 Application of formulas

Without loss of generality, let's consider the scenario where ants start crawling from the origin. When the mth ant of the colony reaches the next target point and is faced with i available paths, the probability formula for the ants' selection of a specific path can be expressed as follows:

$$\phi(i,x_i,t_j)=\frac{\tau(i,x_i,t_j)\eta(i,x_i,t_j)}{\sum\limits_{x_i\geqslant 1}\tau(i,x_i,t_j)\eta(i,x_i,t_j)}$$

where is the selection probability of the ants for the specified traveling path, i is the total number of traveling paths, x_i is the amount of traveling of the ants choosing path i, t_j is the traveling period of the ants, τ is the amount of information, and η is the visibility of the information.

When the ants follow all the paths to complete an iterative behavior, the minimum function of the crawl distance and the amount of information is recorded, from which the parameter relative optimal solution can be obtained. The objective function of the ant colony in the crawling process is calculated as:

$$\left.\begin{aligned} J&=\int_0^\infty(\omega_1|e|+\omega_2U^2+\omega_3|e|)dt+\omega_it, e<0\\ J&=\int_0^\infty(\omega_1|e|+\omega_2U^2)dt+\omega_it, e\geqslant 0\end{aligned}\right\}$$

where e is the colony, J is the objective function of the colony during the crawling process, ω is the crawling parameter, and U is the time constant.The output expression J is used as a mapping of the PID control function of the quadrotor UAV.

6 Results Showcase

The above model is validated by simulation using simulink and the results are shown below:

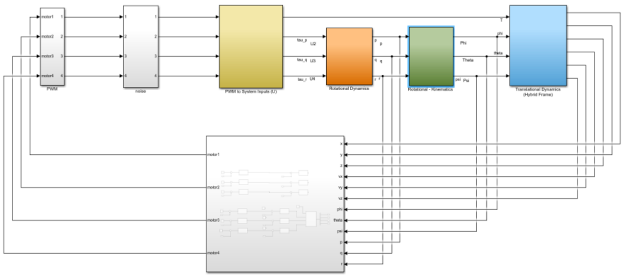

Fig. 6.1 Overall flow chart of Simulink simulation

Figure 6.1 illustrates the simulation flowchart that incorporates classical PID control into the quadrotor UAV dynamics model using Simulink. Each module within the flowchart represents the UAV dynamics equations discussed in Chapter 3. These modules are interconnected through differential and integral relationships. Additionally, an oscilloscope can be configured to visualize the simulation waveform graphs at each stage.

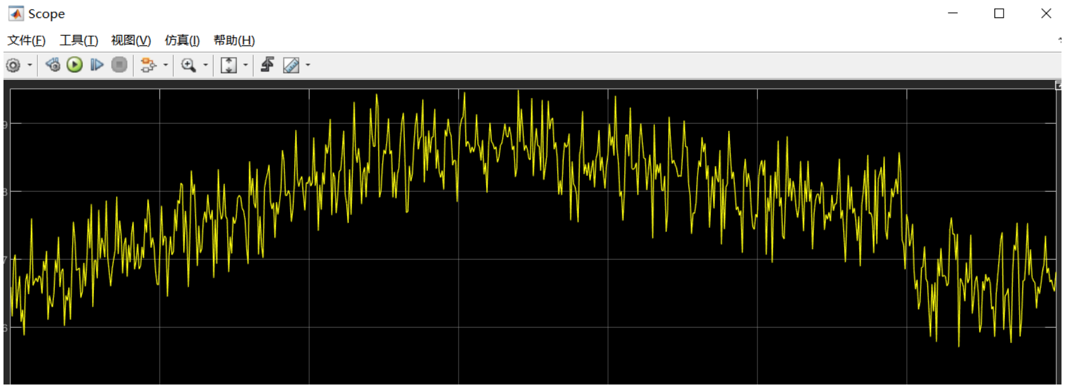

Fig. 6.2 Simulation results of wind speed modeling

According to the results after the principle analysis, the natural wind, gust wind, gradual wind and random wind were simulated with functions, and then integrated with the signal integration component to get the wind disturbance simulation results graph, the noise has a strong interference to the system.

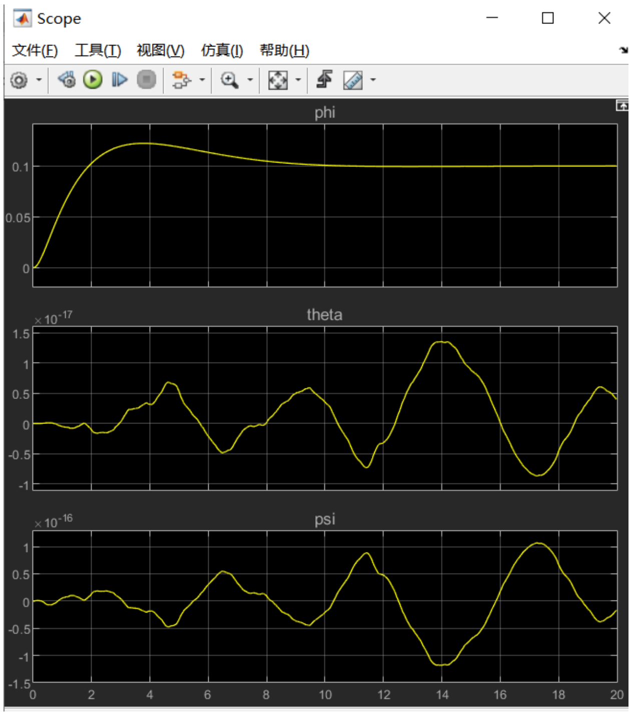

Fig. 6.3 Simulink simulation result plot

The result of fuzzy PID control combined with ant colony algorithm is shown in Fig. 6.3 and it can be seen from the figure that the effect is better and there is a strong control of the motion system of the quadrotor UAV.

7 Concluding Remarks

In this paper, a fuzzy PID control method based on ant colony algorithm for quadrotor UAV under wind disturbance conditions is proposed, and the feasibility of the method is verified through simulation experiments, which can effectively reduce the influence of perturbation and stabilize the motion pattern.

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