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Based on the Intelligent Flight Control System under External Wind Disturbance

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Abstract. Quadrotor Unmanned Aerial Vehicles are being used in numerous domains. However, external disturbances such as wind can cause a decline in the control effect of unmanned aerial vehicles. Hence, this paper mainly focused on the research of algorithms for quadrotors under external wind disturbances. It mainly presents the research on the anti-wind disturbance of three types of intelligent control algorithms for quadrotors, including the classic Proportional-Integral-Derivative (PID) algorithm, the adaptive fuzzy cascade control system based on the PID algorithm, and the ADRC control algorithm. Besides, it introduces the principles of these algorithms and relevant research cases and achievements in areas such as precision agriculture and trajectory control. This paper also analyzes the advantages and disadvantages of these algorithms. The PID algorithm is simple in principle and easy to implement, but it is highly dependent on the system model. The adaptive fuzzy cascade control system based on the PID algorithm does not rely on a definite system model, and it is strongly robust, but the system complexity is high, and parameter tuning is difficult. The ADRC control algorithm has strong anti-interference ability, adaptability, and robustness, but the calculation amount is large, which affects the stability of the system. This paper also presents an algorithm combining the adaptive fuzzy cascade control system based on the PID algorithm with the genetic algorithm, and looks forward to the future research direction and goals.

INTRODUCTION

The quadrotor unmanned aerial vehicle (QUAV) is a type of rotor drone and is widely applied in various fields, including military, civilian, and industrial sectors [1]. In the civilian sector, it can assist in forest fire prevention patrols, aerial transportation, and other tasks, ensuring their successful execution [2]. Yao developed a small drone equipped with a laser radar sensor, capable of exploring complex forest environments in unknown conditions [3]. Shirani et al. proposed a multi-quadrotor drone system model based on a distributed controller with collaborative transportation performance for transporting loads [4]. Additionally, quadrotor unmanned aerial vehicles can also be used in precision agriculture, logistics, distribution and transportation, geological exploration, and other fields. For instance, Valente et al. studied a new algorithm represented by harmony search, which has the capability to optimize path planning and was applied in the precision agriculture management of quadrotor drones [5].

This paper mainly introduces the research on the intelligent control algorithms of three types of quadrotor drones in terms of anti-wind disturbance resistance. They are the classic Proportional-Integral-Derivative (PID) algorithm, the adaptive fuzzy cascade control system based on the PID algorithm, and the Active Disturbance Rejection Control (ARDC) control algorithm. This paper aims to propose algorithms with stronger robustness to address the wind disturbance resistance issue of drones.

MAINBODY

Classic PID Algorithm

PID control is a model-independent or model-lightweight control method that does not rely on the detailed and precise structure of the control system and input/output parameters of the controlled object. Therefore, PID control technology is widely applied in process control.

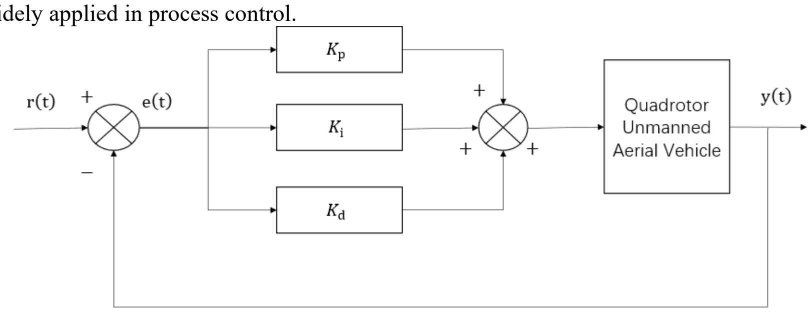

FIGURE 1. Block diagram of pid control system principle [6]

As shown in Figure 1, the standard PID formula for a continuous control system is:

$$u(t) = K_p \cdot e(t) + K_i \cdot \int e\,(t)dt + K_d \cdot de(t)/dt \quad (1)$$

K_p is the gain in proportional control. The larger its value, the faster the system response speed, but it may also cause overshoot and oscillation. K_i is the integral time constant. The larger its value, the smaller the steady-state error, but it will also cause the system response speed to slow down. Kd is the differential time constant. The larger its value, the higher the system stability, but it may cause overshoot. $e(t)$ is the deviation between the given value $r(t)$ and the system output $y(t)$, $u(t)$ is the control output [6].

The quadrotor unmanned aerial vehicles can complete multiple tasks through the PID algorithm. For example, a tethered quadrotor unmanned aerial vehicle combined with cables and winches can achieve simple motion control such as height control through the PID algorithm, while also enabling long-duration flight and operation [7]. The PID algorithm can also be used to take control of the trajectory of each quadrotor unmanned aerial vehicle and calculate its position and velocity, and the attitude controller is designed at points with small roll and pitch, while using pitch and roll to take control of the position in the XY plane. Each quadrotor unmanned aerial vehicle performs formation flight under the control of the sliding mode controller, using a leader-follower structure, with the follower tracking the leader's speed for motion control [8]. In the simulation, the flight trajectories of the leader aircraft and the follower aircraft are similar, actually forming a S-shaped curve. The position error converges quickly and fluctuates around zero after 5 seconds. The error in the yaw angle fluctuates between -0.04 and 0.08 rad in the first 5 seconds, and then fluctuates around zero after 5 seconds [8]. Therefore, this control strategy can achieve a high-precision and stable control effect for the formation of unmanned aerial vehicles.

The classic PID algorithm is simple in principle, easy to implement, and has strong robustness. However, it is difficult to adjust the parameters, and it is highly dependent on the system model. And the integral link is sensitive to outliers.

When encountering external wind disturbances, the PID control algorithm can make the attitude of the quadcopter drone reach the expected goal and ensure the stable flight of the drone. For instance, when the wind causes the quadcopter drone to tilt, the proportional link can be adjusted to return it. During the back-and-forth movement of the drone, oscillations occur. And the oscillations are eliminated through the differential link. If the parameters in the integral link are adjusted appropriately, the response speed of the quadcopter drone will be appropriate throughout the process. However, determining the optimal tuning gain of the PID controller is relatively difficult and requires sufficient time. Moreover, it lacks adaptability and requires manual adjustment of parameters to adapt to changes in the external environment.

In reality, many open-source drone flight control systems basically use cascade PID control. When no external interference is encountered, the cascade PID control system can meet the corresponding requirements and has effectiveness and stability. However, it also has some shortcomings. For example, in outdoor strong winds, the drone will fly for a certain distance in the direction of the wind. After a period of time, the quadcopter drone will slowly return to the center under the effect of the integral link. At this time, if the wind suddenly disappears, due to the value of the integral term in the PID control system was obtained under strong wind conditions, the drone will move in the direction of the wind's original place after the wind disappears and it will take some time to obtain the new value of the integral term. Therefore, improvements of this algorithm or research on other algorithms need to be made.

The Adaptive Fuzzy Cascade Control System Based on the PID Algorithm

The fuzzy adaptive controller combines adaptive control and fuzzy control, based on cascade PID control, to form a control system with unique functions. The fuzzy controller mainly consists of four parts. The fuzzification interface converts the precise values of the input variables into fuzzy values. The knowledge base is divided into a database and a rule base. The inference engine performs fuzzy reasoning from input to output. The defuzzification interface converts the fuzzy quantities into clear control quantities.

Cheng Ben uses a two-dimensional fuzzy controller, selecting the deviation e and the deviation change ec of the controlled object, which can better reflect the dynamic characteristics of the control system. In the fuzzy controller, the fuzzy sets of input and output in the fuzzy controller are selected as [NB, NM, NS, ZO, PS, PM, PB] to describe them as " negative big, negative medium, negative small, zero, positive small, positive medium, positive big " [9], and then it can be transformed from the real domain to the fuzzy domain.

Define the membership degree or membership function. If for any element x in the domain (the range of study) U, there is a number A(x) ∈ [0, 1] corresponding to it, then A is called a fuzzy set on U and A(x) is called the membership degree of x to A. There are various types of membership functions, and here, a triangular membership function is selected, and the formula is as follows:

$$f(x,a,b,c) = \begin{cases} 0 & x \le a \\ \frac{x-a}{b-a} & a \le x \le b \\ \frac{c-x}{c-b} & b \le x \le c \\ 0 & x \ge c \end{cases} \quad (2)$$

Among them, parameters a and c represent the x-coordinates of the triangle, determining the "base" of the triangle. And parameter b is used to represent the y-coordinate of the triangle, determining the "peak" of the triangle [9]. The fuzzy rule base consists of several "IF-THEN" form conditional statements. The values of K_p ,K_i ,K_d should be adjusted according to the differences in the absolute values of e and ec, while corresponding fuzzy rule tables should be formulated.

Fuzzy reasoning is the most crucial part in fuzzy control. There are two commonly used fuzzy conditional reasoning statements: If A then B else C； If A AND B then C. Here, the latter one is chosen. A, B, and C are all fuzzy subsets, where C is the intersection of A and B, and the Mamdani method is adopted [9]. Based on the fuzzy reasoning rules, the ternary fuzzy relation R is determined, and the formula is as follows:

$$C = (A \times B)^T R \quad (3)$$

Where, T is the row vector transformation. After obtaining the fuzzy rules, reverse fuzzification should also be carried out with the weighted average method.

The quadcopter drone controlled by the adaptive fuzzy cascade control system based on the PID algorithm can stabilize the drone under the interference of wind and realize real-time attitude control and trajectory tracking. Its rule base is highly efficient [10]. This algorithm effectively adapts to uncertainty and nonlinearity and does not require a large number of adjustments [11].

Using the unit step signal to simulate the influence of external wind disturbance on the drone, after being interfered by the step signal, the recovery regulation time of the pitch, roll, and yaw angles of the adaptive fuzzy cascade controller is 0.627, 0.627, and 0.620 seconds respectively, and the stabilization time is 0.633, 0.633, and 0.640 seconds [9].

If it is in an indoor environment without wind, as shown in Table 1, using the PID controller to complete the flight trajectory of the aircraft, the maximum and total errors of the aircraft are 0.32 and 8.02 meters respectively, while the aircraft equipped with the self-optimizing fuzzy PID controller has a maximum error of 0.15 meters and a total error of 4.35 meters [10].

TABLE 1. Performance comparison table: equilateral trajectory [10]

Algorithm	Maximum error(m)	Total error(m)
PID	0.32	8.02
Fuzzy-PID	0.15	4.35

The adaptive fuzzy cascade control system based on PID algorithm has made improvements over the classic PID algorithm. It does not rely on a definite system model and can adjust the PID parameters in real time. It also has strong robustness, but the system complexity is high and the parameter tuning is difficult.

In the outdoor strong wind conditions, when a quadrotor unmanned aerial vehicle based on the adaptive fuzzy cascade control system is subjected to uncertain external wind disturbances, the fuzzy controller can perform scale transformation on the input quantity and determine the corresponding membership function. During the control process, continuous flight state information can be obtained based on the operating state of the quadrotor unmanned aerial vehicle. Through the online identification and correction process of the fuzzy unmanned aerial vehicle model, the required fuzzy control rules can be obtained, enabling online fuzzy control rule self-learning, automatic adjustment of the parameters of the fuzzy controller, and control of the quadrotor unmanned aerial vehicle. This significantly improves the adaptability and robustness of the unmanned aerial vehicle. Under the control of this algorithm, the error generated is smaller, and the tracking accuracy is significantly improved [11].

ADRC Control Algorithm

The ADRC control algorithm mainly consists of three parts. The first part is the Tracking Differentiator (TD), which is used to perform tracking differentiation on the input signal. The second part is the Extended State Observer (ESO), which is used to observe and measure various signals such as the unknown part of the model, external unknown disturbances, and other signals in real time. The third part is the Nonlinear State Error Feedback Control Law (NLSEF), which is used to compensate for the generated errors and eliminate the influence of external unknown disturbances such as external wind disturbances.

TD performs tracking differentiation on the input signal. After this dynamic process, the input signal will become smoother. The formula is as follows:

$$\begin{cases} fh = fhan(x_1(k) - v(k), x_2(k), r, h) \\ x_1(k+1) = x_1(k) + h * x_2(k) \quad \text{(Nonlinear)} \\ x_2(k+1) = x_2(k) + h * fh \end{cases} \tag{4}$$

$$\begin{cases} x_1(k+1) = x_1(k) + h * x_2(k) \\ x_2(k+1) = x_2(k) - h * (r^2 * x_1(k) + 2 * r * x_2(k) - r^2 * v) \end{cases} \text{(Linear)} \tag{5}$$

Among this, r represents the tracking speed factor, h represents the oscillation factor, x_1 ,x_2 represent the system's state, $fhan$ is the fastest control synthesis function, and v is the input signal.

ESO designs an extended state quantity, which is derived from the total disturbance of the system, and then the control quantity can be given for compensation.

$$\begin{cases} \varepsilon = z_1 - y \\ \dot{z}_1 = z_2 - \beta_1 \varepsilon \\ \dot{z}_2 = z_3 - \beta_2 fal(\varepsilon, \alpha_{01}, \delta) + bu \\ \dot{z}_3 = -\beta_3 fal(\varepsilon, \alpha_{02}, \delta) \end{cases} \tag{6}$$

Among them, z_1 is the observed value of the system output, z_2 is the observed value of the system output's derivative, and z_3 is the observed value of the total disturbance of the system. β_1 ,β_2 ,β_3 are all observer gains, b is the control gain, ε is the error, u is the final control quantity, and y is the output.

NLSEF is mainly used to compensate for the generated errors. It linearly combines the error signal, the error differential signal, and the error integral signal to achieve linear PID control, and obtains the nonlinear error feedback control law [12]. This controller has various forms. Here, the following form is selected:

$$u_0 = k_1 fal(e_1, \alpha_{11}, \delta) + k_2 fal(e_2, \alpha_{12}, \delta) \tag{7}$$

Here, k_1 ,k_2 are controller gains. Fal function is a nonlinear function.

The ADRC algorithm can be combined with three-axis accelerometers, three-axis gyroscopes, magnetometers, etc. Through the ground station subsystem, it can control the takeoff and landing and other movements of the unmanned aerial vehicle. The three-axis accelerometers and three-axis gyroscopes can be used to measure the acceleration and angular velocity of the object, and the unmanned aerial vehicle uses these parameters related to itself to achieve aerial attitude adjustment. Under the interference of wind, the unmanned aerial vehicle can be used as a remote sensing platform to monitor information such as the growth of agricultural crops and soil conditions [13]. Conducting control accuracy experiments on the unmanned aerial vehicle, with a flight height of 20m and an average wind speed of 3m/s, the results show that the pitch angle control error is within ±4° , the flight height control error is within ±0.86m, and the total flight path control error is less than 1.5 meters. The experimental results indicate that the ADRC algorithm can achieve higher control accuracy in complex environments, effectively ensuring the stability and reliability of the unmanned aerial vehicle when performing tasks.

This algorithm has strong anti-interference ability, strong adaptability and high robustness, but the parameter tuning is complex and the calculation volume is large, which affects the stability of the system. When subjected to strong external wind, the ADRC control algorithm tracks the controller to obtain the approximate derivative of the input signal using a relatively simple function, then the extended state observer estimates the disturbance and state of the quadcopter unmanned aerial vehicle, and then performs corresponding compensation based on this value, allowing the quadcopter unmanned aerial vehicle to fly relatively smoothly in the wind and overcome the influence of external wind disturbances on the system. Therefore, the unmanned aerial vehicle system controlled by the ADRC algorithm has a faster response speed, better stability and robustness.

DISCUSSION

Discussion and Analysis

Quadrotor drones can freely change their postures in the air and can achieve indoor and outdoor fixed-point hovering without the need for additional runways or extra space for takeoff and landing.

In terms of frame layout, the main body frames of quadrotor drones are mainly H-shaped, X-shaped and + shaped. The body frame is designed symmetrically and serves as the main support structure of the drone. It can not only improve the lift efficiency in the same structural space but also effectively reduce the interference of the airflow field [14].

Quadrotor drones also have some problems and defects. Since the movement of quadrotor drones involves six degrees of freedom but only has four control inputs, quadrotor drones are underactuated systems and cannot be transformed into fully actuated systems. In practical applications, underactuated systems often face problems such as changes in model parameters and external disturbances. These problems increase the difficulty of control system design and affect the control effect. The application of QUAV depends on the development of technologies such as sensors, so the flight safety of QUAV will also be affected by airflows [15]. Wind disturbance resistance is an important aspect and an inevitable problem in the actual flight of drones. Currently, quadrotor drones often need to perform tasks in complex conditions, such as sea level, and are required to maintain extremely high precision and stability. At this time, external disturbance winds will affect the precise modeling of the drone, and the model has uncertain parts, increasing the difficulty of model establishment. In addition, since quadrotor drones are usually small in size and light in weight, strong winds can more easily disrupt their stability. This is also a side that is rarely studied and paid attention to [16]. At the same time, if there is no corresponding control algorithm, the drone will have difficulty maintaining a stable and expected posture for a long time under strong external wind disturbances, that is, it may be unstable and cannot guarantee good flight quality. Hence, the research on intelligent control algorithms for quadrotor drones under wind disturbance conditions has certain theoretical research significance and practical application value.

Future Research

To further enhance the stability and robustness of quadrotor drones under external wind disturbances, improvements can be made to the PID algorithm and ADRC algorithm, or other algorithms can be studied. By combining the adaptive fuzzy cascade control system based on the PID algorithm with the genetic algorithm, the fuzzy rules in the fuzzy control can be improved through the genetic algorithm. The control rules are encoded accordingly and then concatenated to form a structure similar to a "chromosome".

The wind environment introduces disturbances, and the genetic algorithm can help stabilize the attitude and improve the attitude of the drone. The application of the genetic algorithm in the quadrotor drone control system can help optimize the PID parameters, solve nonlinear problems, and adapt to uncertain models [17]. This algorithm can help find the optimal fuzzy rules, iteratively explore the parameter space without real-time calculation, and enhance the anti-wind disturbance capability of the quadrotor drone, improving the performance of the control system [17].

CONCLUSION

In recent years, QUAVs have received increasing attention. This paper mainly introduces the research on the anti-wind disturbance of three types of intelligent control algorithms for quadrotors, including the classic PID algorithm, the adaptive fuzzy cascade control system based on PID algorithm and the ADRC control algorithm. It presents research cases and achievements of these algorithms in precision agriculture and trajectory control, etc. It analyzes the movement of QUAVs under wind disturbance and the advantages and disadvantages of each algorithm. Moreover, it proposes a method of combining the adaptive fuzzy cascade control system based on PID algorithm with genetic algorithm. This algorithm can effectively improve the stability and robustness of UAVs under external wind disturbance, and better adapt to the dynamic changes of the system. It outperforms the optimized controller in terms of response speed, overshoot, and steady-state error. In future research, this algorithm will be further improved to enhance the performance of QUAVs.

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