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Attitude Control and Trajectory Tracking of a Shipboard Quadrotor Unmanned Aerial Vehicle Based on Self-Improvement Algorithm

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Abstract:

With the rapid development of Industry 4.0 and urbanisation around the world, computer control technology and electromechanical systems, the development of UAVs around the world has entered a period of rapid development. As UAVs enter the rapid development stage, higher requirements are placed on the precise control rate during UAV missions. Multi-rotor UAVs have been used on ships in large scale due to their easy-to-manoeuvre characteristics. However, shipboard UAVs are affected by many factors during flight, such as crosswinds, gusts and wave effects at sea. Therefore, it is necessary to optimise the robustness and safety of the control process of shipborne UAVs through self-immunity algorithms. In the research process of UAV, modern control theory has developed very rapidly, but it is difficult to be applied in practice, and there is a certain gap. The reason for this is that advanced control theory techniques require an accurate mathematical model of the controlled object.

In this study, the position and attitude equations of motion of the quadrotor UAV are firstly obtained according to the rigid body mechanics, the UAV dynamics model is deduced, and for the UAV attitude control and trajectory tracking requirements, the inner loop adopts the self-immobilisation control and the outer loop adopts the PID control, and the relevant control structure is designed. Through relevant Simulink simulation and comparison with the effect of traditional PID control, the optimisation effect of the self-immunity algorithm on the control of shipborne quadrotor UAV is verified.

Keywords: component; carrier-based drone; self-immunity algorithm; quadcopter drone; attitude control; position tracking

1. Introduction

UAV control simulation can simulate the UAV flight process more realistically through experimental means, based on the change of object-related parameters in the simulation software, it can provide a better theoretical basis for UAV control research and improve the control effect in the UAV flight process.

Quadrotor UAVs are relatively simple in structure and have the advantage of being highly manoeuvrable and easier to control. Therefore, they are widely used in shipboard operations. Due to the complexity of the maritime environment, wind resistance is a key concern for shipborne UAVs [1]. The development of control theory has gone through three stages: classical control, modern control and intelligent control [2]. Control methods such as PID control, backstepping, sliding mode control, and neural networks have been applied to attitude control and position control for quadrotor flight control [3]. The traditional PID control technique does not meet the current control requirements, so optimising the control performance of UAVs by means of self-immunity algorithms is the research objective of this study.

This study is based on MATLAB Simulink, a simulation software, analyses the flight principle of the quadcopter UAV and establishes the machine dynamics model, and adopts the combination of self-immunity and PID control, to avoid the control mode is too narrow, and then according to the specific environmental conditions of the shipborne UAV to obtain the simulation results of the whole machine, and based on the analysis of the data and the effect of the traditional PID control for comparison. Then the simulation results of the whole UAV are obtained according to the specific environmental conditions of the shipborne UAV, and compared with the traditional PID control effect according to the data analysis to verify the optimisation effect of the self-immunity algorithm on the UAV control performance and anti-jamming ability.

2. Mathematical Modelling

2.1 Composition and flight principles of quadcopter drones

Quadcopter UAVs are widely used in the military field because they are suitable for most mission types and application scenarios, and they do not affect the control effect due to the wear and tear of parts during flight. Quadcopter UAVs are mainly composed of control motors, power supplies, propellers, and control modules. The change of position and attitude of the quadcopter is mainly obtained by adjusting the brushless motors and thus changing the rotation speed of the propellers. Each rotor generates a lift force perpendicular to the rotor surface and a counter-torque moment opposite to the direction of rotation [4]. In this study, the quadcopter UAV propeller distribution adopts an ‘X’ symmetrical distribution, and the relevant physics model is established according to the shape data and structural parameters of the shipboard UAV.

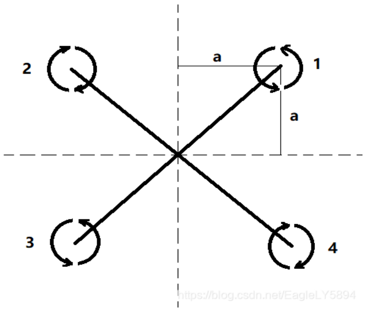

Figure 1: X-type quadcopter

In this design, it is assumed that the structural parameters of the quadrotor UAV are shown in Table 1:

Table 1: Parameters related to UAV simulation

	parametric	numerical value
Quality of drones	m	$1.2kg$
Diagonal length of drone fuselage	l	$0.45m$
gravitational acceleration (physics)	g	$9.8m/s^2$
Position air resistance coefficient	$K_{1,2,3}$	0.02
Attitude air resistance coefficient	$K_{4,5,6}$	0.01
X-axis moment of inertia	I_{xx}	$0.017kg \cdot m^2$
Y-axis moment of inertia	I_{yy}	$0.017kg \cdot m^2$
Z-axis moment of inertia	I_{zz}	$0.004kg \cdot m^2$

2.2 rigid body dynamics (RBD) model

Quadrotor UAVs are nonlinear, complex, underdriven mechanical systems [5]. The following assumptions are assumed to exist in modelling the nonlinear kinematics:

· The UAV is assumed to be a rigid body whose mass and moment of inertia do not change with time during autonomous take-off;

· The acceleration of gravity is assumed to be constant;

· It is assumed that the effects of the curvature, rotation and revolution of the Earth are ignored and are considered flat;

· The ground is assumed to be an inertial reference system, i.e., ground coordinates are assumed to be inertial coordinates;

· Assume a geometrically symmetric distribution of the structure and mass of the UAV and its inertial product $I_{xy} = I_{zy} = 0$.

2.3 UAV positional and attitude equations of motion

In the modelling process the UAV motion process will be defined and described by the transformation between the coordinate systems and the laws of rigid body mechanics to define and describe the UAV flight process.

In this study, the ground coordinate system is specified to have the centre of gravity of the UAV in flight as the origin, and the nose facing direction is specified to be the positive direction of the X-axis, horizontally to the left to be the positive direction of the Y-axis, and vertically fuselage up to be the positive direction of the Z-axis. The fuselage coordinate system takes the centre of gravity of the UAV and its flight as the origin, and the positive direction of X-axis and Z-axis is the same as that of the ground coordinate system, while the positive direction of Y-axis and the direction of the UAV's pitch angle θ, roll angle φ, and yaw angle ψ are determined by the right-hand rule.

· Based on the body coordinate system, R_B^E is utilised to represent the transformation matrix of the body around the X, Y and Z axes with the following formula:

$$R_\theta = \begin{bmatrix} cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & cos\theta \end{bmatrix} \tag{1-1}$$

$$R_\varphi = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\varphi & -\sin\varphi \\ 0 & \sin\varphi & cos\theta \end{bmatrix} \tag{1-12}$$

$$R_\psi = \begin{bmatrix} cos\psi & -\sin\psi & 0 \\ \sin\psi & cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1-3}$$

$$R_B^E = R_\theta R_\varphi R_\psi \tag{1-4}$$

The following equation can be obtained by the Newton-Euler method:

$$m\ddot{X} = R_B^E \sum_{i=1}^{4} F - n_3 \dot{X} - mg \tag{1-5}$$

where $X = \begin{bmatrix} x & y & z \end{bmatrix}^T$ is the translational position of the UAV's centre of gravity, n_3 is the translational drag coefficient, and g is the gravitational acceleration.

· According to the laws of rigid body mechanics it can be concluded that the external moment of the rotor blades is the product of the angular acceleration and its moment of inertia on the axis.

The angular momentum H of the quadrotor is shown below:

$$H = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{1-6}$$

where I_{xx}, I_{yy}, I_{zz} correspond to the moment of inertia in the three directions of the coordinate axis.

Treating $\Omega = \begin{bmatrix} p & q & r \end{bmatrix}^T$ and H^R as the rate of change of angular momentum, the total external moment M is shown below:

$$M = \Omega \times H + H^R \tag{1-7}$$

This is obtained by substituting angular momentum into the above equation and transforming:

$$\begin{cases} \dot{p} = \left[M_X - \left(I_{zz} - I_{yy} \right) qr \right] I_{xx}^{-1} \\ \dot{q} = [M_Y - \left(I_{xx} - I_{zz} \right) rp] I_{yy}^{-1} \\ \dot{r} = \left[M_Z - \left(I_{yy} - I_{xx} \right) pq \right] I_{zz}^{-1} \end{cases} \tag{1-8}$$

The quadrotor attitude angular velocity is:

$$\begin{cases} \ddot{\varphi} = \left[M_x - \dot{\theta}\dot{\psi} \left(I_z - I_y \right) qr \right] I_{xx}^{-1} \\ \ddot{\theta} = \left[M_y - \dot{\varphi}\dot{\psi} \left(I_x - I_z \right) rp \right] I_{yy}^{-1} \\ \ddot{\psi} = \left[M_z - \dot{\varphi}\dot{\theta} \left(I_y - I_x \right) pq \right] I_{zz}^{-1} \end{cases} \tag{1-9}$$

$$\begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix} + \begin{bmatrix} -I_R q \left(-\omega_1 + \omega_2 - \omega_3 + \omega_4 \right) \\ I_R p \left(-\omega_1 + \omega_2 - \omega_3 + \omega_4 \right) \\ 0 \end{bmatrix} \tag{1-10}$$

In the above equations, M_1, M_2, M_3 correspond to the moments of the traverse, pitch and yaw channels of the quadrotor UAV mathematical model, $-I_R q(-\omega_1 +$

$\omega_2 - \omega_3 + \omega_4)$ and $I_R p(-\omega_1 + \omega_2 - \omega_3 + \omega_4)$ are the moments generated by the spin process of the quadrotor UAV, I_R is the rotational inertia of the motors, and l is the quadrotor distance from the centre of gravity of the UAV to the centre of the body.

According to the above assumed conditions and the mutual transformation between coordinate systems, the dynamics and attitude kinematics equations in the take-off process are derived as:

$$\begin{cases} \ddot{x} = \frac{n_1}{m}\left(\sin\varphi\sin\psi + \sin\theta cos\varphi\right)\sum_{i=1}^{4}\Omega_i^2 - \frac{n_{3x}}{m}\dot{x} \\ \ddot{y} = \frac{n_1}{m}(-cos\psi\sin\varphi + \sin\theta cos\varphi\sin\psi)\sum_{i=1}^{4}\Omega_i^2 - \frac{n_{3y}}{m}\dot{y} \\ \ddot{z} = \frac{n_1}{m}\left(cos\theta cos\varphi\right)\sum_{i=1}^{4}\Omega_i^2 - \frac{n_{3z}}{m}\dot{z} - g \\ \ddot{\varphi} = [n_1 l\left(\omega_4^2 - \omega_2^2\right) - I_R q(-\omega_1 + \omega_2 - \omega_3 + \omega_4)\dot{\theta}\dot{\psi}\left(I_z - I_y\right)]I_{xx}^{-1} \\ \ddot{\theta} = [n_1 l\left(\omega_3^2 - \omega_1^2\right) + I_R p\left(-\omega_1 + \omega_2 - \omega_3 + \omega_4\right) - \dot{\varphi}\dot{\psi}\left(I_x - I_z\right)rp]I_{yy}^{-1} \\ \ddot{\psi} = [n_2(\omega_2^2 + \omega_4^2 - \omega_1^2 - \omega_3^2) - \dot{\varphi}\dot{\theta}\left(I_y - I_x\right)]I_{zz}^{-1} \end{cases} \#(1-11) \qquad (1\text{-}11)$$

3. Control Programme Design

Analysing the working environment of the shipborne quadcopter UAV is the key to designing the control scheme, and safety is the control objective in the flight process, and its substantive objective is to control the shipborne UAV to maintain a stable flight state with a safe attitude and a reduced speed under the interference. The shipborne UAV is susceptible to the influence of the sea wind factor during the working process, and the design of the relevant control scheme is carried out in order to improve the UAV's wind resistance and anti-interference ability during the working process.

3.1 Introduction to the control programme

Self- Impedance control is able to observe the internal and external disturbances in the system in real time [6] and compensate for them, and it has a certain anti-jamming ability to suppress the unknown disturbances in the system by the way of 'observation+compensation'. The self-immunity controller consists of three parts: tracking-differentiator (TD), extended state observer (ESO) and nonlinear state feedback (NLSEF). Its system structure is shown in Figure 2:

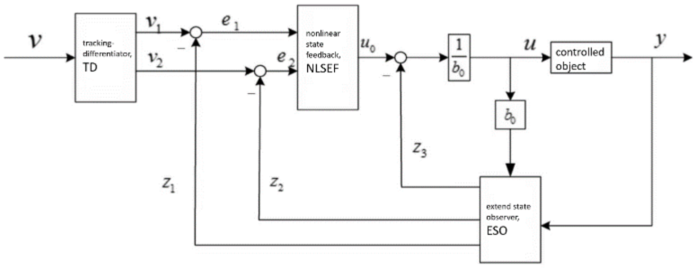

Figure 2: Structure of self-resistant controller

PID is nowadays widely used in control systems, but it is not able to keep the UAV running at a low speed in the case of interference. The traditional PID control has the following technical defects:

· it is not reasonable to generate error by directly subtracting the feedback signal from the given value;
· here is no good way to extract the error differential;
· the linear combination is not necessarily the best combination;
· the introduction of the error integral feedback will make the system lagging and prone to oscillations.

Therefore, for the operating environment of shipborne UAVs, the self-immunity algorithm has good applicability. In this study, in order to control the attitude and trajectory of the shipborne quadrotor UAV, the inner loop adopts the self-immunity control and the outer loop adopts the PID control in the control scheme.

3.2 Inner Loop Attitude Controller Design

For the flight control process of the shipborne quadrotor UAV, its control of the UAV mainly involves three loops: yaw, roll and pitch. In this thesis, the main focus is on the analysis of the cross-roll angle channel and the derivation to other circuits.

· Tracking Differential: Input signal ‘softening’ process, then output differential signal and smooth tracking signal. It is designed as follows:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -l \cdot sign(e + \frac{x_2|x_2|}{2l} \end{cases} \tag{2-1}$$

Where x_1, x_2 are the input signals.

· Expanded state observer: real-time estimation of perturbations and corresponding compensation can effectively measure and track system inputs in real time, and in this way determine the total system perturbations and the internal state information of the system. Its design is as follows:

$$\begin{cases} e = z_1 - \varphi \\ \dot{z}_1 = z_2 - \beta_1 \cdot e \\ \dot{z}_2 = z_3 - \beta_2 \cdot fal(e, a_1, \delta) + b_0 u \\ \dot{z}_3 = -\beta_3 \cdot fal(e, a_2, \delta) \end{cases} \tag{2-2}$$

$$fal(e, a, \delta) = \begin{cases} \frac{e}{\delta^{1-a}}, |e| \leqslant \delta \\ |e|^a sign(e), |e| > \delta \end{cases} \tag{2-3}$$

where the observed effects of x_1, x_2 are z_1, z_2 ,and z_3 is the observed value of the full perturbation.

· Nonlinear state error feedback controller: the input signal is obtained by tracking the tracking signal and its differential signal through the tracking differentiator, and the estimated value obtained by expanding the state observer, which can be obtained by subtracting the error signal and its differential signal. When the error signal is small, the feedback gain should be large, and vice versa. It is designed as follows:

$$\begin{cases} e_1 = x_1 - z_1 \\ e_2 = x_2 - z_2 \\ u_0 = k_1 fal(e_1, a_3, \delta) + k_2 fal(e_2, a_4, \delta) \end{cases} \tag{2-4}$$

where k_1, k_2 are adjustable parameters.

3.3 Outer loop trajectory tracking PID control design

In order to improve the control effect of the quadcopter UAV in practical use, the traditional PID control is used in the control of trajectory tracking, which can overcome the problem of too many parameters of the self-immobilising controller and improve the control efficiency. Designing in this way enables the UAV to be adjusted at a higher speed when it is far from the intended trajectory, i.e. when the error is large, and to be adjusted smoothly at a lower speed when the error is small.

The design was carried out by means of an XYZ three-direction inertial coordinate system:

$$\begin{cases} \ddot{x} = K_{px}(x_d - x) + K_{ix}\int(x_d - x)dt + K_{dx}(\dot{x}_d - \dot{x}) \\ \ddot{y} = K_{py}(y_d - y) + K_{iy}\int(y_d - y)dt + K_{dy}(\dot{y}_d - \dot{y}) \\ \ddot{z} = K_{pz}(z_d - z) + K_{iz}\int(z_d - z)dt + K_{dz}(\dot{z}_d - \dot{z}) \end{cases} \tag{2-5}$$

Also to find the linear velocity in the UAV body coordinate system in the ideal case:

$$\begin{bmatrix} p_d \\ q_d \\ r_d \end{bmatrix} = R_B^E \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} \tag{2-6}$$

where p_d, q_d, r_d are the linear velocities in the desired body coordinate system; R_B^E is the transformation matrix.

From this, the acceleration in the XYZ direction can be found for the ideal case:

$$\begin{cases} a_x = K_{pp}(p_d - p) + K_{pi}\int(p_d - p)dt + K_{pd}(\dot{p}_d - \dot{p}) \\ a_y = K_{qp}(q_d - q) + K_{qi}\int(q_d - q)dt + K_{qd}(\dot{q}_d - \dot{q}) \\ a_z = K_{rp}(r_d - r) + K_{ri}\int(r_d - r)dt + K_{rd}(\dot{w}_d - \dot{r}) \end{cases} \tag{2-7}$$

where a_x, a_y, a_z are the three-direction desired line acceleration control quantities corresponding to the coordinate axes.

The desired roll angle control quantity φ_r, pitch angle control quantity θ_r and Z-axis control quantity total distance δ_{col} can be approximated by the three-direction desired line acceleration control quantity.The related control quantities are shown in the following equations:

$$\begin{cases} ma_x = -mg\sin\theta \approx -mg\theta \\ ma_y = mg\sin\varphi cos\theta \approx mg\varphi \\ ma_z = mgcos\theta cos\varphi - u_{col} \end{cases} \tag{2-8}$$

Simplification leads to:

$$\begin{cases} \theta_r = -\frac{a_x}{g} \\ \varphi_r = \frac{a_y}{g} \\ u_{col} = mgcos\theta cos\varphi - ma_z \end{cases} \tag{2-9}$$

4. Matlab Simulink Platform Simulation

In the actual simulation process, the simulation model is constructed according to the above obtained formula, which is used as an experimental object, and its reasonableness is verified through the Simulink simulation platform, and the control effect of the traditional PID controller is compared to verify its effectiveness. The feasibility and accuracy of the designed self-immunity controller are verified through Simulink simulation.

4.1 Build simulation models

In this controller design, the corresponding wind field interference system is established for the working environment of the shipboard UAV, the trajectory tracking module, the attitude control module provide flight control, the power provision relies on the motor module, the controlled object quadcopter UAV, the wind field module is composed of the Discrete Wind Gust Model in Simulink in conjunction with other components. The self-resistant control is used as the inner loop for attitude control, and the PID control is used as the outer loop for trajectory tracking. The wind field system and simulation results are shown in Figure 3, 4:

Figure 3: Wind field simulation module

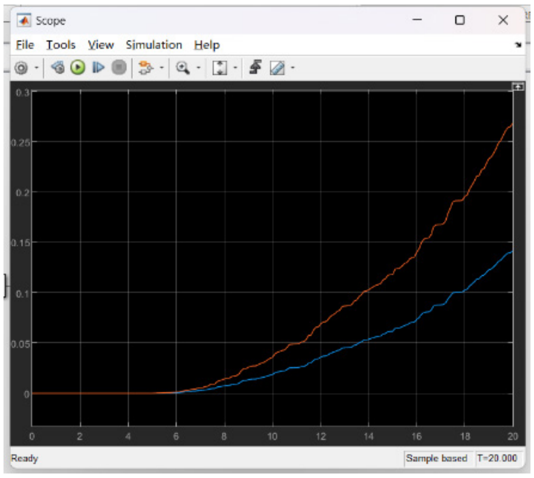

Figure 4: Wind field simulation effect

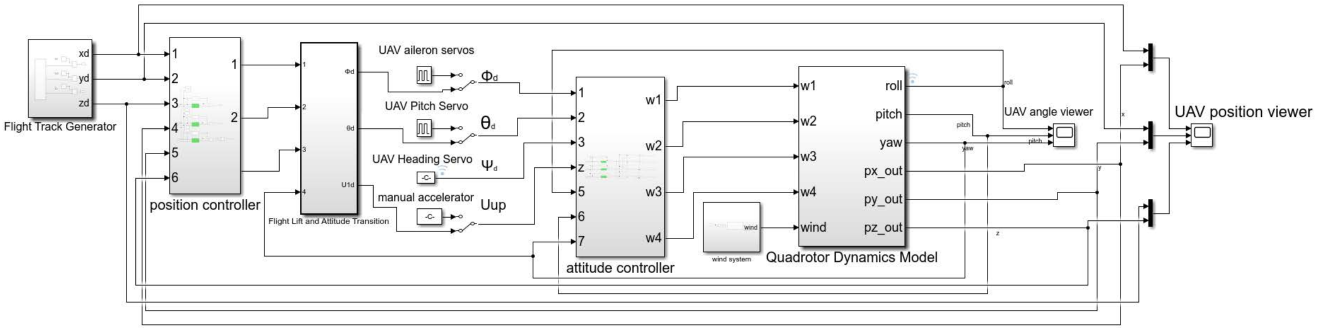

Figure 5: Quadcopter UAV control structure

4.2 UAV Attitude Response Analysis

The operation process of the shipborne quadcopter UAV is affected by many factors, such as gusts, side winds and waves and other disturbances, so it is necessary to include similar disturbance signals in the simulation process. The interference of gusts is similar to rectangular pulse disturbance, the interference of waves is similar to random interference, and step signal interference and sinusoidal signal disturbance are also added to simulate other interference factors. In this case, the flight process of the shipborne UAV is simulated, and when the UAV is under gust interference, i.e., the controller is under the influence of rectangular pulse perturbation, its attitude angle response is shown in the following figure:

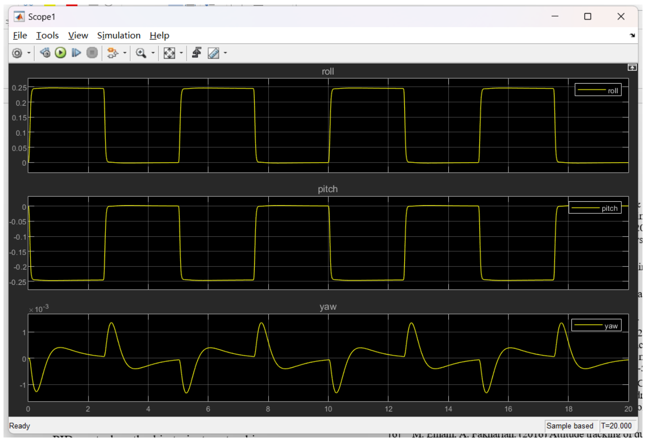

Figure 6: Attitude Angle Response

4.3 UAV trajectory tracking simulation

In the trajectory tracking simulation process, the desired trajectory is generated to reflect the control accuracy, and the PID control and the control method used in this study are used to compare the effect.

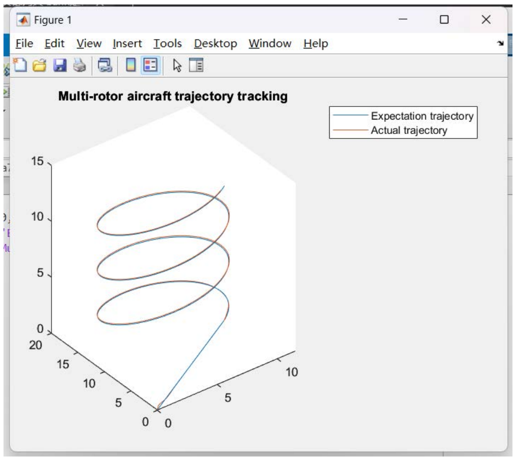

Figure 7: Trajectory tracking effect of the control method in this study

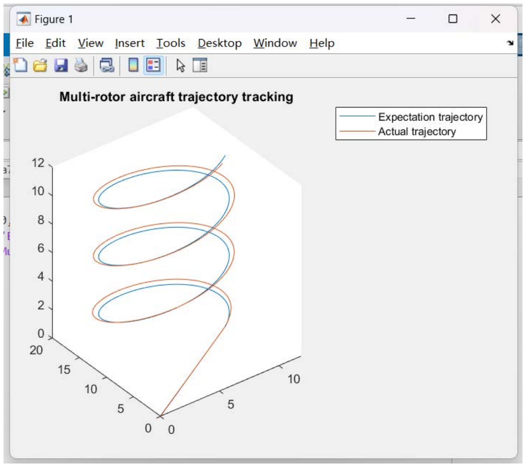

Figure 8: Trajectory tracking effect of PID control

According to the simulation effect comparison, it can be found that the UAV control method proposed in this study, the UAV running trajectory and the target trajectory error is smaller, and the control effect is better than the traditional PID control method in trajectory tracking.

5. Summary

In this study, mathematical modelling of the UAV is carried out, the principle as well as the composition of the self-immunity controller is introduced in detail, and the self-immunity control technology is combined with the attitude control of the UAV, and then the joint PID position control is used to build a simulation model in Matlab/Simulink, and the simulation experiments are carried out, and then the result graphs derived from the simulation process are analysed to get the controller's performance of controlling in the flight process of the UAV and the anti-jamming ability of the system, and its control performance and wind-resistant effect are proved.

References

[1] Morariu, A. R., Ahmad, T., Iancu, B., Poikonen, J., & Björkqvist, J. (2024, May). Analysing MLOps and its Applicability in the Maritime Domain through a Systematic Mapping Study. In 2024 IEEE 7th International Conference on Industrial Cyber-Physical Systems (ICPS) (pp. 1-8). IEEE.

[2] Zixing C. (2018) 40 years of intelligent control in China. Science & Technology Review, 36(17): 23-39.

[3] Li, Y. , Song, S. (2012). A survey of control algorithms for Quadrotor Unmanned Helicopter. IEEE Fifth International Conference on Advanced Computational Intelligence. IEEE.

[4] Ling Zhao, Liuwei Dai, Yuanqing Xia, Peng Li. (2019) Attitude control for quadrotors subjected to wind disturbances via active disturbance rejection control and integral sliding mode control. Mechanical Systems and Signal Processing, 129: 531-545.

[5] Mauricio Alejandro Lotufo, Luigi Colangelo, Carlos Perez-Montenegro, Enrico Canuto. (2019) UAV quadrotor attitude control:An ADRC-EMC combined approach. Control Engineering Practice, 84: 13-22.

[6] M. Emam, A. Fakharian. (2016) Attitude tracking of quadrotor UAV via mixed H2/H∞ controller: An LMI based approach. In: Mediterranean Conference on Control and Automation. Athens. 390-395.