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Research on Flight Control of Quad-rotor Based on Backstepping and Adaptive Control Technology

Congbo Luo

Changchun University of Science and Technology, Changchun,China
luocongbo13@163.com

Abstract

According to the uncertainty problem in the process of quad-rotor aircraft flight, As close to the actual flight environment, The nonlinear dynamic model of quad-rotor aircraft is established,On the basis of the backstepping, Analyzed the presence of interference control quantity expression and adaptive law.This paper puts forward a technique of backstepping and adaptive control technology,Through Matlab simulation and flight test of the designed adaptive inverse footwork the effectiveness of the proposed controller is verified, The simulation results show that the system has good robustness.

Keywords*: Quad-rotor;Nonlinear model, Matlab Simulation, Backstepping and adaptive control technology*

1. Introduction

In recent years, the quad-rotor with its characteristics of low cost, high performance, unique structure and the way of flight, gradually become a hot point of attention at home and abroad, the quad-rotor is widely used in military and civil field. The quad-rotor is a kind of unmanned aerial vehicle rotorcraft, the main feature is the ability to vertical take-off and landing and free hovering.

Typical micro quad-rotor attitude control system respectively to the longitudinal, lateral and directional three channels for coordinated control, to realize automatic flight. Because of the UAV has nonlinear, strong coupling and weak anti-interference ability, and in different environment and large inclination, rapid inclination rate cases, poor stability of flight characteristics, makes flight control becomes very difficult. At present, many research institutions and universities at home and abroad related research, on the four rotor aircraft flight control, is a typical method with PID control, linear quadratic optimal control, sliding mode control, the backstepping control and dynamic inversion h-infinity control and so on. Among them, the sliding mode control method to bring the system chattering phenomenon, PID control can't adjust the parameter online.

According to the above problem, this paper designed the four rotor aircraft controller based on adaptive inverse footwork, four rotor aircraft dynamics model is established and simplified; On the basis of the footwork, design the adaptive inverse controller footwork, estimate the uncertainty of system on-line, has carried on the anti-jamming simulation and flight test, the design is verified by the effectiveness and robustness of the algorithm.

2. Nonlinear Mathematical Model of Quad-Rotor

Figure 1 for four rotor aircraft structure, four rotor aircraft is four motor installed in a cross-shaped cross structure four-terminal rigidity, four rotor aircraft with six degrees of freedom, but only by the four rotor at the end of the crossed structure produce driving force, is a kind of underactuated, strong coupling, multivariable and nonlinear complex system.

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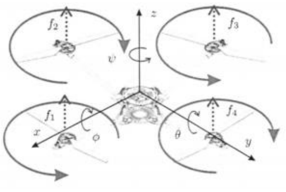


Figure 1. Illustrates the Four Rotor Aircraft Structure

For six degree of freedom of four rotor aircraft, the dynamics equation of the Newton - Euler formula method, the dynamic equation of system will be derived. Considering the four rotor aircraft model and control algorithm research convenience, simplify the complexity of the problem, put forward the following assumptions: 1) the body structure and rotor as a rigid body, ignore the elastic deformation and vibration; 2) the vehicle mass center and the body coordinate system origin is consistent, thought the ground coordinate system as the inertial coordinate system, ignoring the earth curvature and rotation; 3) in addition to the airflow produced by the rotation of propeller, air flow velocity is zero; 4) four motor and propeller symmetrically installed on the four side of the cross rigidity, and at the same level. Position and attitude Angle of the simplified system model is set up as follows:

$$\begin{cases} \ddot{x} = (\cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi)\dfrac{U_1}{m} \\ \ddot{y} = (\sin\psi\sin\theta\cos\phi - \cos\psi\sin\phi)\dfrac{U_1}{m} \\ \ddot{z} = (\cos\theta\cos\phi)\dfrac{U_1}{m} - g \\ \dot{p} = \dfrac{I_{yy} - I_{zz}}{I_{xx}} qr - \dfrac{J_{TP}}{I_{xx}} q\Omega + \dfrac{U_2}{I_{xx}} \\ \dot{q} = \dfrac{I_{zz} - I_{xx}}{I_{yy}} pr - \dfrac{J_{TP}}{I_{yy}} p\Omega + \dfrac{U_3}{I_{yy}} \\ \dot{r} = \dfrac{I_{xx} - I_{yy}}{I_{zz}} pq + \dfrac{U_4}{I_{zz}} \end{cases} \tag{1}$$

Among them, x, y, z, respectively four rotor aircraft navigation coordinates in x, y, and z axis displacement, ϕ, θ, ψ respectively four rotor aircraft in the navigation system of pitch attitude Angle, roll attitude Angle, yaw attitude Angle; m says four rotor aircraft overall quality; Four rotor lift and U1 said, U2 said four rotor aircraft pitch direction torque, U3 said the direction of the four rotor aircraft roll torque, U4 said the direction of the four rotor aircraft yaw moment; The algebraic sum of said four rotor speed; p, q, r, respectively four rotor aircraft carrier in the axial velocity of coordinates; It indicates that the rotor of the rotary inertia; *Ixx, Iyy, Izz* respectively four rotor aircraft around the x, y, z axes rotational inertia.

3. Quad-Rotor Adaptive Inverse and Backstepping Controller

Many practical control systems, such as aircraft control system, tank control system, control system of induction motor, such as electro-hydraulic servo system is a nonlinear system, and often there are many uncertainties in nonlinear systems. These uncertainties include mathematics model of parameter uncertainty and unmodeled dynamics and external interference and white noise, etc., so that the actual controlled object and there was a big difference in the established mathematical model, the control of the system is put forward higher requirements. Four rotor aircraft aerodynamic environment complex, the motor rotating the existence of strong vibration, there are the external environment disturbance, this paper based on the Backstepping method combined with adaptive control technology to processing of the uncertainty of the flight control system, in order to improve the anti-interference ability of the flight control system and robust performance.

3.1 Adaptive Inverse and Backstepping Design Train of Thought

To illustrate the designing idea of the adaptive inverse footwork, below to strict feedback form of nonlinear systems with unknown constant, for example:

$$\begin{cases} x_1 = x_2 + \theta x_1{}^2 \\ x_2 = u \end{cases} \qquad (2)$$

Type (2) the x1, x2 for system state variables, u for system input variables, theta is often unknown parameters.To coordinate transform, the definition

$$\begin{cases} z_1 = x_1 \\ z_2 = x_2 - \alpha_1 \end{cases} \qquad (3)$$

Type (3) the alpha α_1 as virtual control, is the x_2 estimates.
Step 1: design for z_1 subsystem.

$$\dot{z}_1 = \dot{x}_1 = x_2 + \theta x_1{}^2 \qquad (4)$$

See x_2 as virtual control quantity, and if you take the , the z1 subsystem is stable, theta is unknown, however, so only alpha 1 to replace the x2, design for α_1

$$\alpha_1 = -c_1 z_1 - \hat{\theta}_1 x_1{}^2 \text{ (Constant } c1 > 0\text{)} \qquad (5)$$

Among them, $\hat{\theta}_1$ is θ first estimates. Remember to ,$\tilde{\theta}_1 = \theta - \hat{\theta}_1$, $z_2 = x_2 - \alpha_1$.

$$\begin{aligned} \dot{z}_1 &= x_2 + \theta\, x_1{}^2 = z_2 + \alpha_1 + \theta\, x_1{}^2 \\ &= z2 - c_1 z_1 + (\theta - \hat{\theta}_1) x_1{}^2 \end{aligned} \qquad (6)$$

Select the first subsystem of Lyapunov function $V_1 = \frac{1}{2} Z_1{}^2 + \frac{1}{2} \tilde{\theta}_1{}^2$, for the

$$\begin{aligned} \dot{V}_1 &= z_1 \dot{z}_1 - \tilde{\theta}_1 \dot{\hat{\theta}}_1 \\ &= z_1 (z_2 - c_1 z_1 + \tilde{\theta}_1 x_1{}^2) - \tilde{\theta}_1 \dot{\hat{\theta}}_1 \\ &= z_1 z_2 - c_1 z_1{}^2 + \tilde{\theta}_1 (z_1 x_1{}^2 - \dot{\hat{\theta}}_1) \end{aligned} \qquad (7)$$

From the adaptive control law

$$\dot{\hat{\theta}}_1 = z_1 x_1{}^2 \qquad (8)$$

Type(8) into type (7), in the making. z1z2 items will in the next step of design was off, but the first subsystem is stable.
Step 2: ask the system real control law u.

$$\begin{aligned} \dot{z}_2 &= \dot{x}_2 - \dot{\alpha}_1 \\ &= u - (-c_1 \dot{z}_1 - \dot{\hat{\theta}}_1 x_1^2 - 2\theta_1 x_1 \dot{x}_1) \\ &= u + c_1 (x_2 + \theta x_1^2) + z_1^5 + 2\hat{\theta}_1 z_1 (x_2 + \theta x_1^2) \end{aligned} \qquad (9)$$

$\hat{\theta}_2$ is defined by the θ of a second estimate of theta.Remember to $\tilde{\theta}_2 = \theta - \hat{\theta}_2$.
Take the system control law for

$$u = -z_1 - c_2 z_2 - c_1 (x_2 + \hat{\theta}_2 x_1^2) - z_1^5 - 2\theta_1 z_1 (x_2 + \theta_2 x_1^2) \quad (c_2 > 0) \qquad (10)$$

An adaptive law is selected

$$\dot{\hat{\hat{\theta}}}_2 = z_1^2 z_2 (c_1 + 2\theta_1 z_1) \qquad (11)$$

Choose the Lyapunov function of the whole system is $V_2 = V_1 + \frac{1}{2} z_2{}^2 + \frac{1}{2} \tilde{\theta}_2{}^2$, for the

$$\begin{aligned} \dot{V}_2 &= \dot{V}_1 + z_1 \dot{z}_2 - \tilde{\theta}_2 \dot{\hat{\theta}}_2 \\ &= -c_1 z_1^2 - c_2 z_2^2 + \tilde{\theta}_2 [z_1^2 z_2 (c_1 + 2\hat{\hat{\theta}}_1 z_1) - \dot{\theta}_2] \\ &= -c_1 z_1^2 - c_2 z_2^2 \end{aligned} \qquad (12)$$

By choosing suitable convergence parameters c1, c2, c3, can make the system (2) to achieve globally asymptotically stable. Adaptive against the gait design and the basic and the gait design different is: to estimate the uncertainty of system parameters online, real-time adjustment, and expand the Lyapunov function is used to ensure the stability of the system.

3.2 The Implementation of the Adaptive Inverse Controller and Backstepping

Fly in the real environment, four rotor is always the moderating effect of the external environment as well as the uncertainty of parameters, to comprehensively consider the uncertainty of the system for D. We need to online estimation of D, D adaptive law with the footwork. For location subsystem, when there is interference, its dynamic equation is expressed as

$$\begin{cases} m\ddot{x} = u_x U_1 + D_x \\ m\ddot{y} = u_y U_1 + D_y \\ m\ddot{z} = \cos\phi \cos\theta U_1 - mg + D_z \end{cases} \qquad (13)$$

Type(13), $D_i = (i = x, y, z)$ is the uncertainty of three axes respectively,

$$u_x = \sin\theta \cos\phi \cos\psi + \sin\phi \sin\psi$$

$$u_y = \sin\theta \cos\phi \sin\psi - \sin\phi \cos\psi \qquad (14)$$

With high channel z as an example, and the state equation is expressed as again

$$\begin{cases} \dot{x}_7 = x_8 \\ \dot{x}_8 = \dfrac{1}{m}(\cos x_3 \cos x_1 U_1 - mg + D_z) \end{cases} \qquad (15)$$

Type(15), $x_7 = z, x_8 = \dot{z}, x_1 = \phi, x_3 = \theta$, D_z for interference on the z axis direction of uncertainty.Because the D_z is unknown, Need to estimate online, Define the D_z estimate of,Write for estimation error is : $\tilde{D}_z = D_z - \hat{D}_z$.

The heights expected of a given $z_d = x_{7d}$,Defines the height error variable $z_7 = x_7 - x_{7d}$,Velocity error variables $z_8 = x_8 - \alpha_7$ .Among them, for the virtual control amount.

Step 1: the subsystem design.

$$\dot{z}_7 = \dot{x}_7 - \dot{x}_{7d} = x_8 - \dot{x}_{7d} \qquad (16)$$

Type (16), x_8 will be considered a control volume,if $x_8 = \dot{x}_{7d} - c_7 z_7$, z_7 subsystem is asymptotically stable. Butis the middle state variables, can only use α_7 instead of x_8,Designed to be $\alpha_7 = \dot{x}_{7d} - c_7 z_7 \ (c_7 > 0)$.

Select the first Lyapunov function subsystem $V_7 = \frac{1}{2} z_7{}^2$,For the

$$\begin{aligned} \dot{V}_7 &= z_7 \dot{z}_7 = z_7 (x_8 - \dot{x}_{7d}) \\ &= z_7 (z_8 + \alpha_7 - \dot{x}_{7d}) \\ &= z_7 z_8 - c_7 z_7{}^2 \end{aligned} \tag{17}$$

Type (17), $z_7 z_8$ will be in the design of the next step was to drop, make $\dot{V}_7 < 0$, the first subsystem is stable.

Step 2: practical control law and adaptive control law.For the $\dot{z}_8 = \dot{x}_8 - \ddot{x}_{7d} + c_7 \dot{z}_7$, $V_8 = \frac{1}{2} z_8{}^2 + V_7$ define the Lyapunov function,For the

$$\begin{aligned} \dot{V}_8 &= z_8 \dot{z}_8 + \dot{V}_7 = z_8 (\dot{x}_8 - \ddot{x}_{7d} + c_7 \dot{z}_7) - c_7 z_7{}^2 + z_7 z_8 \\ &= z_8 [\dot{x}_8 - \ddot{x}_{7d} + c_7 (z_8 - c_7 z_7)] - c_7 z_7{}^2 + z_7 z_8 \\ &= z_8 [\frac{1}{m} (\cos x_3 \cos x_1 U_1 - mg + D_z) - \ddot{x}_{7d} + c_7 (z_8 - c_7 z_7)] \\ &\quad - c_7 z_7{}^2 + z_7 z_8 \end{aligned} \tag{18}$$

Type (18), take system control is

$$U_1 = \frac{m}{\cos x_3 \cos x_1} (\ddot{x}_{7d} - z_7 - c_8 z_8 - c_7 z_8 + c_7{}^2 z_7 + g) - \frac{D_z}{m} \tag{19}$$

Type (19), as a result of D$_z$ is unknown, replace with its estimate, can be expressed as

$$U_1 = \frac{m}{\cos x_3 \cos x_1} (\ddot{x}_{7d} - z_7 - c_8 z_8 - c_7 z_8 + c_7{}^2 z_7 + g) - \frac{\hat{D}_z}{m} \tag{20}$$

Type (20) in order to find out the adaptive law, expand the Lyapunov function is $V_8 = V_7 + \frac{1}{2} z_8{}^2 + \frac{\hat{D}_z{}^2}{2m\lambda} \ (\lambda > 0)$,The first derivative of it is

$$\begin{aligned} \dot{V}_8 &= \dot{V}_7 + z_8 \dot{z}_8 - \tfrac{1}{m\lambda} \tilde{D}_z \dot{\hat{D}}_z \\ &= -c_7 z_7^2 - c_8 z_8^2 + \tfrac{1}{m} z_8 (D_z - \hat{\hat{D}}_z) - \tfrac{1}{m\lambda} \tilde{D}_z \dot{D}_z \\ &= -c_7 z_7^2 - c_8 z_8^2 + \tfrac{\tilde{D}_z}{m} (z_8 - \tfrac{1}{\lambda} \dot{\hat{D}}_z) \end{aligned} \tag{21}$$

The estimate of type selection (21) adaptive law $\dot{\hat{D}}_z = \lambda_1 z_8 \ (\lambda_1 > 0)$,So as to make the Lyapunov function of the whole system $\dot{V}_8 = -c_7 z_7{}^2 - c_8 z_8{}^2 < 0 \ (c_7, c_8 > 0)$,System can guarantee the error variable $z_7, z_8, \hat{D}_z$ index is asymptotically stable.

In the same way, using adaptive inverse footwork to horizontal position exists interference D$_x$,D$_y$ equation, get adaptive control volume:

$$\begin{cases} u_x = \dfrac{m}{U_1} [\ddot{x}_{9d} + (c_9{}^2 - 1) z_9 - (c_9 + c_{10}) z_{10} - \dfrac{\dot{D}_x}{m}] \\ u_y = \dfrac{m}{U_1} [\ddot{x}_{11d} + (c_{11}{}^2 - 1) z_{11} - (c_{11} + c_{12}) z_{12} - \dfrac{\dot{D}_y}{m}] \end{cases} \tag{22}$$

The adaptive law is:

$$\begin{cases} \dot{\hat{D}}_x = \lambda_2 z_{10} \\ \dot{\hat{D}}_z = \lambda_3 z_{12} \end{cases} (\lambda_2 > 0, \lambda_3 > 0) \tag{23}$$

Type (22) and type (23),

$$z_9 = x - x_d = x_9 - x_{9d} \quad z_{11} = y - y_d = x_{11} - x_{11d}$$
$$z_{10} = x_{10} - \dot{x}_{9d} = +c_9 z_9 \quad z_{12} = \mathrm{x}_{12} - \dot{\mathrm{x}}_{11\mathrm{d}} + c_{11} z_{11} \tag{24}$$

According to the type (14) nonlinear constraint relation between variables, we can get

$$\begin{cases} \phi_d = \arcsin(u_x \sin\psi - u_y \cos\psi) = \arcsin(u_x \sin x_5 - u_y \cos x_5) \\ \phi_d = \arcsin[\dfrac{(u_x - \sin\phi \sin\psi)}{\cos\phi \cos\psi}] = \arcsin[\dfrac{(u_x - \sin x_1 \sin x_5)}{\cos x_1 \cos x_5}] \end{cases} \tag{25}$$

Will type (22-24) into type (25) respectively, the expectation of the inner ring roll Angle and pitching Angle can be obtained.

4. The Simulation Experiment and Result Analysis

Step to verify that the adaptive inverse control algorithm, the feasibility and effectiveness of Matlab/Simulink simulation experiment. Set the vehicle's initial state is respectively: euler Angle (o. 524,0.524, 0.524)rad ; Euler Angle velocity (0.2.0.2, 0.2)rad/s: location (0, 0, 0) m; Linear velocity (0, 0, 0) m/s. Control targets for inertial coordinate system origin (0, 0) from the ground to the desired target location (1,1,1) and maintain stable hover. Expect yaw Angle of 0 rad . Model parameters such as Table 1, the controller parameters for: cl = l0, c2 = 3, c3 = 5, c4 = 8, c5 = 3, c6 = 2; c7 = c8 = c9 = c10 = c11 = c12 = 4,. The following simulation experiment and result analysis.

Table 1. Model Parameters of the Four Rotor Aircraft

Parameter	*Symbol*	*Value*	*unit*
Lift coefficient	b	3.13e-5	$N \cdot s^2$
Drag coefficient	d	7.5e-7	$N \cdot ms^2$
Rotational inertia of the x axis	Ix	6.228e-3	$kg \cdot m^2$
Rotational inertia of the y axis	Iy	6.228e-3	$kg \cdot m^2$
Rotational inertia of the z axis	Iz	1.121e-2	$kg \cdot m^2$
Center of mass to the distance of the rotor	l	0.232	m
Total mass of aircraft	m	0.53	kg

4.1 Fixed Point of the Flight

Set the attitude Angle of the three initial value are $\phi = \theta = \psi = 0.524 rad/s$: target location for the flight x= y = z = 1 m, the simulation time for t = 15 s. The change of the posture and position under the above parameters curve as shown in figure 2.

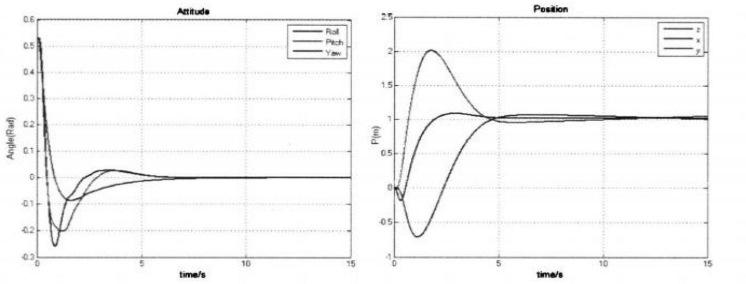


Figure 2. Flying Posture and Position Change Curve

By figure 2 can see, aircraft finally reach the target location near(1, 1, 1), the steady-state error is small, the attitude Angle of 0 rad, almost all system step in the adaptive inverse control algorithm to be able to complete the specified point and keep hovering flight missions, and fly more smoothly. Can be seen from the graph the curve of the relatively small amount of overshoot and adjustment time is shorter, reverse gait adaptive control convergence speed, the dynamic effect is more ideal.

4.2 Anti-Interference Analysis

Adaptive inverse footwork is mainly exist in the actual flight test environment of the system all kinds of uncertainty, so the anti-interference experiment on it. Considering the uncertainty of external disturbance, such as motor vibration, wind) on the system, the influence of the position of the aircraft, posture, and the corresponding linear velocity and angular velocity change. Anti-interference simulation experiment was carried out.

1)At t = l0s, 15s, 20s to linear velocity dx, dy, dz direction in turn with a rectangular wave for the mutation interference signal, the signal amplitude is 0.5 m/s, pulse width is 0.2 s, the simulation results as shown in figure 3.

2)At t = 10, 15, 20 s s s to the attitude Angle, and, in turn, plus a rectangular wave as a direction interference emergency signal, signal amplitude is 0.1 rad and pulse width for o. 2 s, the simulation results are shown in figure 4.

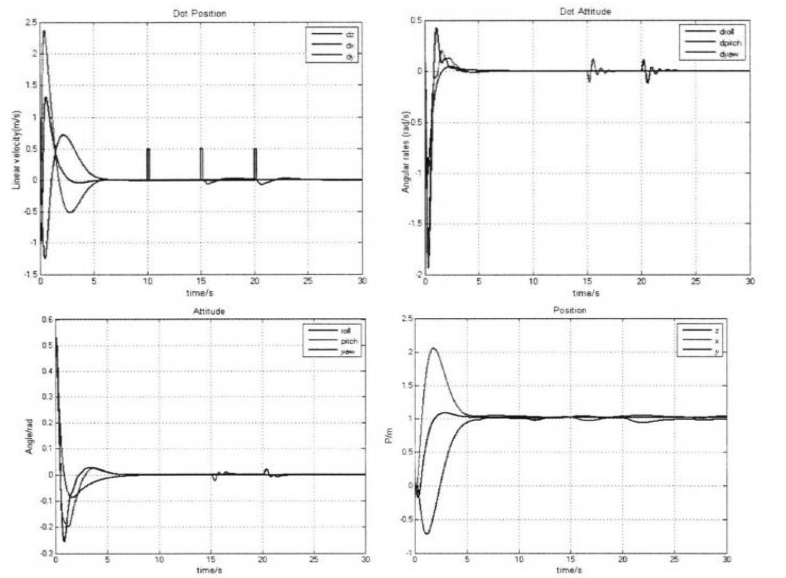
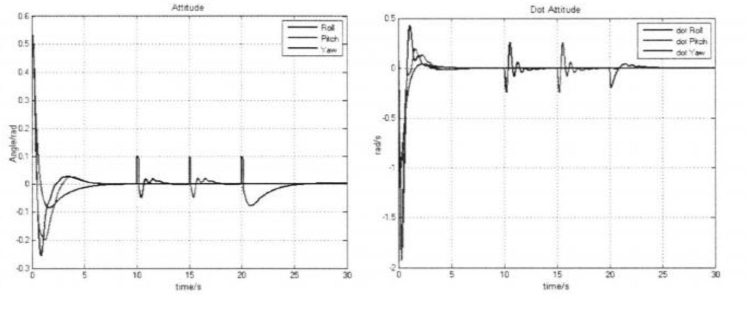


Figure 3. Linear Velocity and Interfere with the Simulation Results



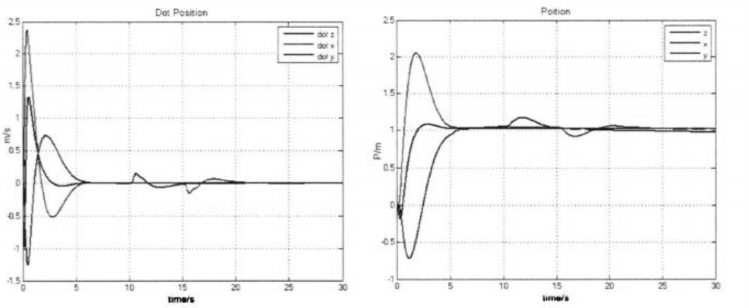


Figure 4. Attitude Angle and Interfere with the Simulation Results

3)At t = l0s to plus a amplitude in the angular velocity of 0.5 rad , the pulse width of 0.2 s rectangular wave as the interference signal: sudden at t = 15 s angular velocity plus a value of 0.5 rad/s pulse width is 0.2 s rectangular wave as the interference of sudden signal; In t = 20 s to angular velocity plus a value of 0.5 rad/s pulse width is 0.2 s of rectangular wave as the interference signal. The simulation results are shown in figure 5.

4)At t = 10, 15, 20 s s s to the attitude Angle when z, x, y direction with a rectangular wave as in turn interference sudden signal, signal amplitude is 0.2 m, width of 0.2 s, the simulation result is shown in figure 6.

Through the above four simulation experiment shows that on the state variables of mutation signal, respectively, and the variable phase coupling of state variables will have corresponding change, but in the quickly time back to the original state of stable hover. Also shows that system coupling structure relationship: z associated with dz, associated with, x associated with dx, associated with, y associated with dy. By the graph, you can see that system after the interference can be returned to the stable position within 3 s, specification design of process control system not only has good dynamic and steady state error, but also has a certain anti-interference ability.

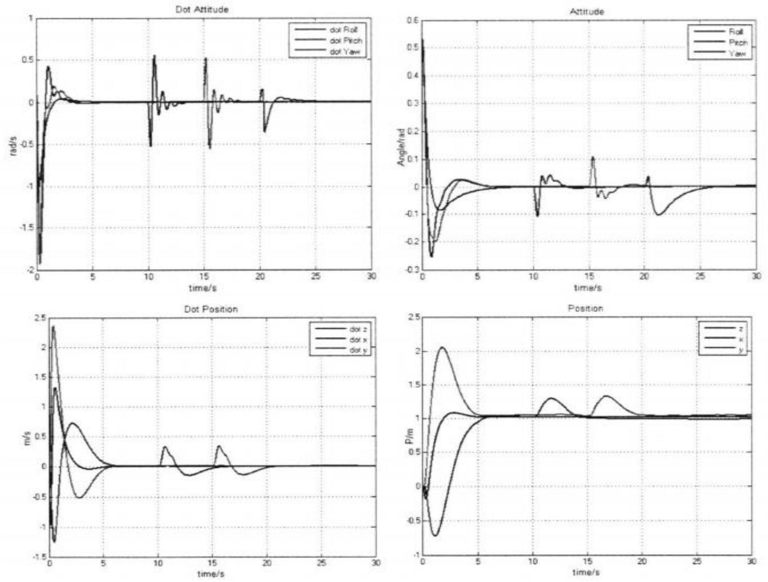


Figure 5. Angular Velocity and Jamming Signal Simulation Results

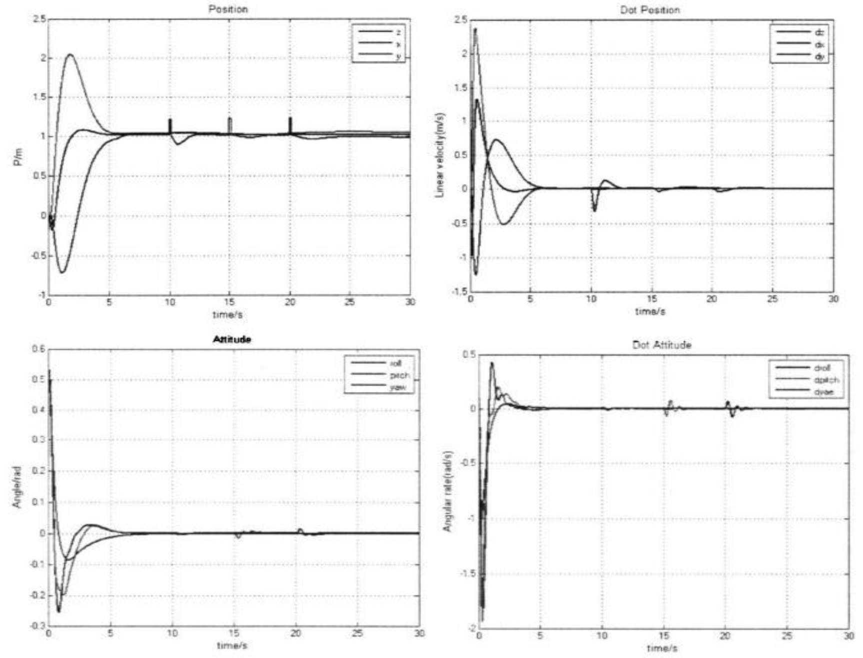


Figure 6. Position Plus Interference Simulation Results

5. Flight Test

Considering the results of simulation and the actual real flight, there is a difference, in order to verify the feasibility of the adaptive inverse controller footwork, in this article, through their own design and production of four rotor aircraft flight test (shown in figure 7) and finally determine the various parameters through field test.

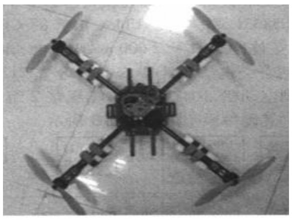


Figure 7. Quad-Rotor Real Figure

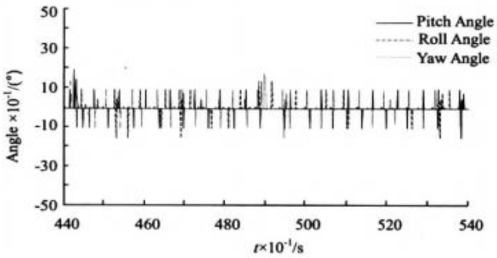


Figure 8. Test Results of the Flying Experiment

Aircraft in the air posture by the angular velocity sensor data acquisition and transmission through Bluetooth devices to the machine. Test results as shown in figure 8, four rotor aircraft at 44 s lift-off, 44 s to 54s in the air, 54 pitching Angle rolling Angle and the Angle of the course Angle change is very small (less than 5 °). The results showed that the adaptive inverse control can adjust the footwork spacecraft attitude changes due to disturbances such as wind.

6. Conclusion

This article mainly take into account the actual environment, the system there are many uncertainties, flight by reverse footwork combined with adaptive control technology, design a new step of adaptive inverse control law, and has carried on the simulation and flight tests. Results show that the proposed control algorithm of fixed-point flight has good dynamic performance, as well as the outside interference has good robust performance.

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