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Adaptive Backstepping Sliding Mode Trajectory Tracking Control for a Quad-rotor

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Abstract: A quad-rotor aircraft is an under-actuated, strongly coupled nonlinear system with parameter uncertainty and un-modeled disturbance. In order to make the aircraft track the desired trajectory, a nested double-loops control system is adopted in this paper. A position error proportional-derivative (PD) controller is designed as the outer-loop controller based on the coupling action between rotational and translational movement, and an adaptive backstepping sliding mode control algorithm is used to stabilize the attitude. Finally, both the numerical simulation and prototype experiment are utilized to demonstrate the effectiveness of the proposed control system.

Keywords: Quad-rotor, nested double-loops, coupling action, adaptive backstepping, sliding mode.

1 Introduction

Quad-rotor consisting of four individual rotors of "X" arrangement is a vertical taking-off and landing unmanned aircraft. This aircraft has a potentially simpler configuration compared with a conventional helicopter since the slopes of its blades are not controlled but the speed of the four rotors are controlled[1]. And it can be used in many fields such as surveillance, search, rescue, scout and so on. For these reasons, the control and design of this mini aerial robots have received much attention within the automatic control community throughout the last decade[2].

The quad-rotor aircraft is an under-actuated, strong coupled non-linear system. To deal with these questions, the backstepping technique has been introduced into the design of aircraft control system. In [3], a new approach for the attitude control of a quad-rotor aircraft was proposed resting on the combination of the backstepping technique and a nonlinear robust proportional-integral (PI) controller. Madani and Benallegue[4, 5] divided the quad-rotor into three interconnected subsystems and proposed a backstepping controller based on the Lyapunov stability theory to set the aircraft to track three the desired trajectories. Zuo[6] designed a flight control system capable of not only stabilizing attitude but also tracking a trajectory using a new command-filtered backstepping technique and a linear tracking differentiator.

The purpose of this paper is to design a flight control system forcing the quad-rotor aircraft to track the reference trajectory. In this paper, considering the under-actuated and strong coupling characteristics of a quad-rotor, the closed-loop aircraft control system is treated as a nested double-loops structure system, with the outer-loop indicating the relationship between translation and rotation movement, and the inner-loop representing the attitude dynamics. A position error proportional-derivative (PD) linear feedback controller is designed in the outer-loop to export the desired attitude angles to the inner-loop. In the inner-loop, with respect to the uncertain moment of inertia and un-modeled disturbance, an attitude stability augmentation controller is proposed based on the adaptive backstepping sliding mode control (ABSM) technique to track the attitude commanded signal produced by the outer-loop. This ABSM method was developed by Koshkouei and Zinober[7], combining the advantages of adaptive backstepping[8] and sliding mode[9] methods. The adaptive law is used to estimate the uncertain parameters, and the sliding mode to compensate the un-parameterizable disturbance. At each step of this back-stepping method, the virtual control variable can be obtained by the Lyapunov stability theory. A sliding-surface defined in terms of the errors of each steps is incorporated into the Lyapunov function at the final step. And according to the special structure of uncertain parameters in the dynamic model, a modification is also introduced into the Lyapunov function in this paper.

The whole paper is organized as follows. Section 2 presents the dynamic model of a quad-rotor aircraft. The trajectory tracking flight control system is proposed in Sections 3. The inner-loop attitude stability controller and the out-loop position PD controller are designed, respectively, in this section. In Section 4, the result of numerical simulation indicates that the quad-rotor tracks the desired trajectory accurately and rapidly. The prototype aircraft experiment partially verifies the utility of the control system in Section 5. Finally, the conclusions of the proposed trajectory tracking control algorithm are presented in Section 6.

2 The dynamic model

The scheme of quad-rotor helicopter is shown in Fig. 1, where Ω_i, $i = 1, 2, 3, 4$ are the speeds of four rotors, respectively. The front and rear rotors are rotary count-clockwise with the other two are rotary clockwise. When the rotor speeds are varied together with the same quantity, the lift force will change[5]. The yaw movement is obtained by in-

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creasing (reducing) the speed of the front and rear rotors and reducing (increasing) the same speed of the lateral rotors depending on the desired angle direction. The roll angle is obtained by increasing (reducing) the speed of the rear rotor and reducing (increasing) the speed of the front rotor. The roll angle is obtained similarly using the lateral motors. And the translation according to axes (X or Y) depends on the change of attitude angles (pitch or roll).

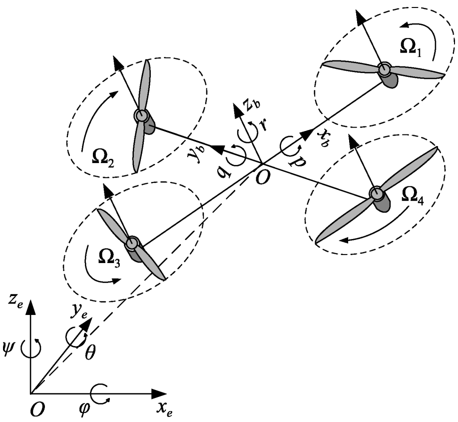


Fig. 1 The scheme of a quad-rotor aircraft with the front and rear rotors rotating counter-clockwise and the other two clockwise

The equations describing the attitude and translation of a quad-rotor aircraft are basically those of a rotating rigid body with six degrees of freedom, which can be derived by using Newton-Euler formulas. Some aerodynamic effects such as vortex ring state, blade flapping caused by the differing inflow velocities and the effect caused by the quad-rotor body in the slip stream of the rotors can be ignored at low speed. Under certain assumptions, the system can be decoupled in two independent but connected subsystems, the first one is related to the translational position and the second one concerns the rotational angles.

Let E denote the earth-fixed inertial frame, and B denote a body-fixed frame with their origins at the centre of the quad-rotor. The translational position of the quad- rotor is defined as $P = [x, y, z]^{\mathrm{T}}$, and the attitude is expressed by the Euler angles $\eta = [\phi, \theta, \psi]^{\mathrm{T}}$.

The rotational dynamic equations of quad-rotor can be obtained by using the Newton-Euler equation, such as

$$\frac{\mathrm{d}H}{\mathrm{d}t} = \frac{\delta H}{\mathrm{d}t} + \omega \times H = M + \delta M \tag{1}$$

where $\omega = [p, q, r]^{\mathrm{T}}$ denotes the angular velocity with respect to the frame B, and $H = J \cdot \omega$ is called as the angular momentum with $J = \mathrm{diag}[I_x, I_y, I_z]^{\mathrm{T}}$ representing the rotational inertia of the quad-rotor. The torque provided by the rotors is represented by M, and the variable δM denotes the un-modeled disturbance torque, which satisfies $\|\delta M\| \leqslant h$ with h as a known upper bound.

From all above, the rotational dynamic model (1) can be represented as

$$J\dot{\omega} = \omega \times J\omega + M + \delta M. \tag{2}$$

The rotational kinematics equations which represent the relationship between the angular velocity ω and the Euler rates $\dot{\eta}$ are complicated for they are from different coordinate systems and it can be represented as

$$\dot{\eta} = W \cdot \omega \tag{3}$$

where the relationship matrix W is defined in [6], and when the pitch angle $\theta \neq \pm\pi/2$, the matrix W is invertible.

For the total lift force F produced by the rotors and the rotational relationship matrix R between frame B and frame E, the translational dynamic equations of the quad-rotor can be represented as

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = \begin{bmatrix} \dfrac{F(\cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi) + \delta F_x}{m} \\ \dfrac{F(\sin\psi\sin\theta\cos\phi - \cos\psi\sin\phi) + \delta F_y}{m} \\ \dfrac{F\cos\theta\cos\phi + \delta F_z}{m - g} \end{bmatrix} \tag{4}$$

where δF_i, $i = x, y, z$ represent the un-modeled force.

3 Flight control system

In consideration of the under-actuated and strong coupled properties of a quad-rotor proposed in (2) and (4), the closed-loop aircraft system is divided into two loops. And accordingly, the flight control system consists of a translational controller in the outer-loop and an attitude stability augmentation controller in the inner-loop. The scheme of the quad-rotor system is shown in Fig. 2.

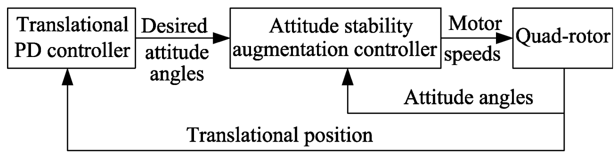


Fig. 2 The double-loops scheme of quad-rotor control system with a translational controller in the outer-loop and an attitude stability controller in the inner-loop

3.1 The translational controller

In this subsection, a position error PD linear feedback controller in the outer-loop will be proposed. It is used to compare the reference trajectory with real position of aircraft and export the desired attitude signals to the inner-loop. The translational equations (4) will be treated as the plant to the controller which exports the desired attitude angles and drag force based on the reference trajectory.

Firstly, three virtual control inputs u_x, u_y and u_z defined as

$$\begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} = \begin{bmatrix} \dfrac{F(\cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi)}{m} \\ \dfrac{F(\sin\psi\sin\theta\cos\phi - \cos\psi\sin\phi)}{m} \\ \dfrac{F\cos\theta\cos\phi}{m} \end{bmatrix}$$

are introduced into the translational equations (4). They can be designed based on the position error PD closed-loop equation of the quad-rotor, such as

$$\begin{cases} u_x = \ddot{x}_d + K_{xd}(\dot{x}_d - \dot{x}) + K_{xp}(x_d - x) \\ u_y = \ddot{y}_d + K_{yd}(\dot{y}_d - \dot{y}) + K_{yp}(y_d - y) \\ u_z = \ddot{z}_d + K_{zd}(\dot{z}_d - \dot{z}) + K_{zp}(z_d - z) \end{cases}$$

where x_d, y_d, and z_d represent the desired position, K_p and K_d are the positive definite control parameters. It is easy to verify that such virtual control inputs can guarantee the aircraft to track the reference trajectory according to the Routh-Hurwitz criterion.

And thus, when the yaw angle is kept at $\phi_d = 0$, according to the relationship between virtual control signals and the attitude angles, the drag force F and desired attitude angles can be proposed as

$$F = m\sqrt{(u_z+g)^2 + u_x^2 + u_y^2} \tag{5}$$

$$\theta_d = \arctan\left(\frac{u_x}{u_z + g}\right) \tag{6}$$

$$\phi_d = -\arcsin\left(\frac{u_y}{F}\right). \tag{7}$$

The vector $\eta_d = [\phi_d, \theta_d, \psi_d]^{\mathrm{T}}$ will be treated as the reference input to the attitude stability augmentation control inner-loop in the next section.

3.2 The translational controller

The attitude stability augmentation controller, employing the adaptive backstepping sliding mode technique, is the base of the aircraft control system. Its task is to keep the yaw angle at $\phi_d = 0$, the pitch and roll angles tracking the desired angles θ_d and ψ_d proposed in the above subsection.

According to the designing procedure of backstepping control algorithm, the tracking error in the fist step is defined as $e_1 = \eta - \eta_d$, and the candidate Lyapunov function V_1 which is positive definite can be represented as

$$V_1 = \frac{1}{2} e_1^{\mathrm{T}} e_1 \tag{8}$$

The time derivative of the Lyapunov function along the trajectory (3) is given by

$$\dot{V}_1 = e_1^{\mathrm{T}}(\dot{\eta} - \dot{\eta}_d) = e_1^{\mathrm{T}}(W \cdot \omega - \dot{\eta}_d).$$

Therefore, the stabilization of e_1 can be obtained by introducing a virtual angular speed command ω_d, which is extracted to satisfy $\dot{V}_1 = e_1^{\mathrm{T}} T_1 e_1 \leqslant 0$, as

$$\omega_d = W^{-1}(T_1 \cdot e_1 + \dot{\eta}_d)$$

where T_1 is a positive definite diagonal matrix.

Define the error variable as $e_2 = \omega - \omega_d$ in the second step, the derivation of error e_1 can be proposed as

$$\dot{e_1} = -T_1 e_1 + W e_2.$$

To provide robustness, the sliding mode algorithm is introduced into this step with the sliding surface defined as $s = e_1 + e_2$. And for the uncertainty of the rotational inertia, an adaptive update algorithm is also employed in this step. The augment Lyapunov function in the second step can be proposed as

$$V_2 = V_1 + \frac{1}{2} S^{\mathrm{T}} J S + \frac{1}{2}(I - \hat{I})^{\mathrm{T}} T_3^{-1} (I - \hat{I}) \tag{9}$$

where $\hat{I}$ is the adaptive estimation of $I = [I_x, I_y, I_z]^{\mathrm{T}}$. And T_3 is the adaptive gain coefficient matrix.

Similarly, taking the time derivative of V_2 along the vector field of (2) and (3) yields

$$\begin{aligned}\dot{V}_2 = {} & e_1^{\mathrm{T}} e_1 + S^{\mathrm{T}} J \dot{S} - (I - \hat{I})^{\mathrm{T}} T_3^{-1} \dot{\hat{I}} = \\ & e_1^{\mathrm{T}}(-T_1 e_1 + W e_2) + S^{\mathrm{T}} J(-T_1 e_1 + W e_2 - \dot{\omega_d}) + \\ & s^{\mathrm{T}}(\omega \times J\omega + M + \delta M) - (I - \hat{I})^{\mathrm{T}} T_3^{-1} \dot{\hat{I}} = \\ & e_1^{\mathrm{T}}(-T_1 e_1 + W e_2) + S^{\mathrm{T}} L(-T_1 e_1 + W e_2 - \dot{\omega_d}) \dot{I} + \\ & s^{\mathrm{T}}(-sk(\omega) L(\omega) + M + \delta M) - (I - \hat{I})^{\mathrm{T}} T_3^{-1} \dot{\hat{I}}\end{aligned}$$

where $sk(\omega)$ is a skew-symmetric matrix, and the linear operator $L(\omega)$ is defined as

$$L(\omega) = \mathrm{diag}\{p, q, r\} \tag{10}$$

i.e., it changes the angular velocity vector into a diagonal matrix. If the control torque is extracted as

$$\begin{aligned} M = {} & -(L(-T_1 e_1 + W e_2 - \dot{\omega_d}) - sk(\omega) L(\omega)) \cdot \hat{I} \\ & - W^{\mathrm{T}} e_1 - T_2 s - \frac{s h^2}{(h\|s\| + \varepsilon \mathrm{e}^{-at})} \end{aligned} \tag{11}$$

and the estimation update law is proposed as

$$\dot{\hat{I}} = T_3 (L(-T_1 e_1 + W e_2 - \dot{\omega_d}) - sk(\omega) L(\omega)) \cdot s \tag{12}$$

where T_2 is a positive definite diagonal matrixes, ε and a are positive coefficients. Substituting (11) and (12) into the time derivative $\dot{V}_2$ yields

$$\dot{V}_2 \leqslant -e_1^{\mathrm{T}}(T_1 + W^{\mathrm{T}}) e_1 - s^{\mathrm{T}} T_2 s + \varepsilon \mathrm{e}^{-at}. \tag{13}$$

Thus, if the attitude angles are bounded in a suitable scope, there will be positive definite diagonal matrixes T_1, T_2 and a parameter c which makes (13) satisfy

$$\dot{V}_2 \leqslant -c(e_1^{\mathrm{T}} e_1 + s^{\mathrm{T}} s) + \varepsilon \mathrm{e}^{-at}. \tag{14}$$

Integrating both sides of the inequality (14) yields

$$V_2(t) - V_2(0) \leqslant -\int_0^t \left(c(e_1^{\mathrm{T}} e_1 + s^{\mathrm{T}} s) + \varepsilon \mathrm{e}^{-a\tau} \right) \mathrm{d}\tau. \tag{15}$$

Then

$$0 \leqslant \int_0^t c(e_1^{\mathrm{T}} e_1 + s^{\mathrm{T}} s) \mathrm{d}\tau \leqslant V_2(0) + \frac{\varepsilon(1 - \mathrm{e}^{-at})}{a} \tag{16}$$

and

$$\lim_{t \to \infty} \int_0^t c(e_1^{\mathrm{T}} e_1 + s^{\mathrm{T}} s) \mathrm{d}\tau \leqslant V_2(0) + \frac{\varepsilon}{a} < \infty.$$

Since $e_1^{\mathrm{T}} e_1 + s^{\mathrm{T}} s$ is a uniformly continuous function, according to the Barbalat Lemma, it holds

$$\lim_{t \to \infty} (e_1^{\mathrm{T}} e_1 + s^{\mathrm{T}} s) = 0$$

which implies $e_1 \to 0$ and $s \to 0$ as $t \to 0$. From the definition of the sliding surface s, it is apparent that $e_2 \to 0$ as $t \to \infty$.

Remark 1. When the moment of inertia of the quad-rotor aircraft is accurately known, the Lyapunov function (9) becomes

$$V_2 = V_1 + \frac{1}{2} s^{\mathrm{T}} s. \tag{17}$$

And the inequality (14) becomes

$$\dot{V}_2 \leqslant -2cV_2 + \varepsilon \mathrm{e}^{-at}. \tag{18}$$

Integrate both sides of (18) leads to

$$0 \leqslant V_2 \leqslant \frac{\varepsilon}{a-2c}(\mathrm{e}^{-2ct} - \mathrm{e}^{-at}) + V_2(0)\mathrm{e}^{-at} \tag{19}$$

which means $\lim_{t\to\infty} V_2(t) = 0$ implying $e_1 \to 0$, $s \to 0$, and $e_2 \to 0$ as $t \to \infty$.

Remark 2. For the function $\int_0^t c(e_1^{\mathrm{T}} e_1 + s^{\mathrm{T}} s)\mathrm{d}\tau$ is bounded, it is deduced that $V_2(t)$ is also bounded from (15). Then the adaptive estimation is bounded. From (9) and (14), based on LaSalle′s invariance theorem, it further follows that the state $(e_1, s, \hat{(I)})$ converges to the largest invariant set N of the closed-loop system contained in

$$E = \{(e_1, s, \hat{I}) | e_1, s = 0)\}$$

i.e., in the set where $\dot{V_2}(0) = 0$. On this invariant set, it has that $e_1 = s = 0$ and $\dot{e_1} = \dot{s} = 0$. Setting them in (12), we obtain $\hat{I} = 0$, and the largest invariant N set in E is

$$N = \left\{ (e_1, s, \hat{I}) \left| \begin{array}{l} e_1, s = 0 \\ \begin{pmatrix} L(-T_1 e_1 + W e_2 - \dot{\omega_d}) \\ -sk(\omega)L(\omega) \end{pmatrix} \cdot (I - \hat{I}) = 0 \end{array} \right. \right\}.$$

If it is satisfied that

$$\mathrm{rank}(L(-T_1 e_1 + T e_2 - \dot{\omega_d}) - sk(\omega)L(\omega)) = 3$$

where 3 is the dimension of I, under the adaptive control law, $\hat{I} \to I$ as $t \to \infty$.

4 The numerical simulation

In this section, in order to verify the validity and efficiency of the control algorithm proposed in this paper, simulations of two typical trajectory tracking tasks are performed on Matlab/Simulink in the presence of uncertain rotational inertia J and external disturbance d. The model date is taken as

$$\begin{aligned} m &= 2.5\,\mathrm{kg} \\ l &= 0.5\,\mathrm{m} \\ k_1 &= 54.2 \times 10^{-6}\,\mathrm{N \cdot s^2} \\ k_2 &= 1.1 \times 10^{-6}\,\mathrm{N \cdot ms^2}. \end{aligned}$$

The initial attitude angles of the quad-rotor are selected as $\psi_0 = 0.2\,\mathrm{rad}$, $\phi_0 = \theta_0 = 0$, and the initial position is $x = y = z = 0$.

The first task is to track an elliptical trajectory as

$$\begin{aligned} x_d &= \sin(\frac{t}{2}) \\ y_d &= 1.2\sin(\frac{t+\pi}{2}) \\ z_d &= 10 \end{aligned}$$

and the yaw angle command is fixed at zero. The quad-rotor flight trajectory is shown in Fig. 3. And the time histories of Euler angles are illustrated in Fig. 4. As expected, the proposed control system is capable of making the aircraft track smooth trajectory in a satisfactory way and guaranteeing the attitude angles stable in an appropriate scope.

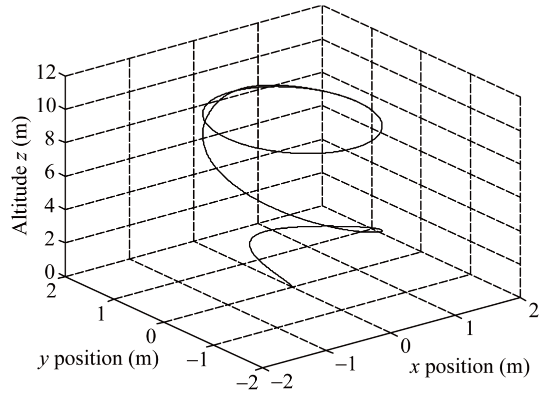


Fig. 3 The circular trajectory tracking result in the first simulation task

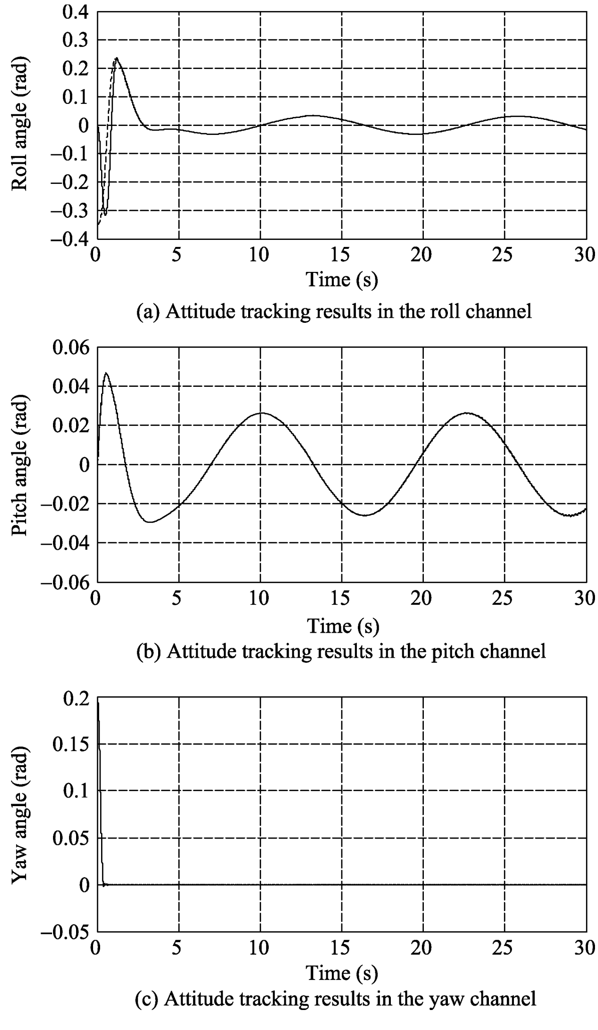


Fig. 4 The tracking performance of the attitude stability controller in the first simulation task with the dashed lines representing the desired attitude commands produced by the translational controller and the solid lines representing the actual attitude angles of the aircraft

In the second simulation, the considered desired trajectory is a horizontal rectangle, given by

$$\begin{cases} x_d = \dfrac{4(t-5)}{5}\mathrm{fsg}(t,5,10) + 4\mathrm{fsg}(t,10,15) + \\ \qquad \dfrac{4(20-t)}{5}\mathrm{fsg}(t,15,20) \\ y_d = \dfrac{3(t-10)}{5}\mathrm{fsg}(t,10,15) + 3\mathrm{fsg}(t,15,20) + \\ \qquad \dfrac{3(25-t)}{5}\mathrm{fsg}(t,20,25) \\ z_d = \dfrac{3t}{5}\mathrm{fsg}(t,0,5) + 3\mathrm{fsg}(t,5,30) \end{cases}$$

where the function $\mathrm{fsg}(\cdot)$ is an interval function and expressed as

$$\mathrm{fsg}(x,a,b) = \frac{\mathrm{sgn}(x-a) + \mathrm{sgn}(b-x)}{2}.$$

Figs. 5 and 6 depict the performance of trajectory tracking and the Euler angles, respectively. They verify the proposed control system has the same efficiency to track different trajectory types.

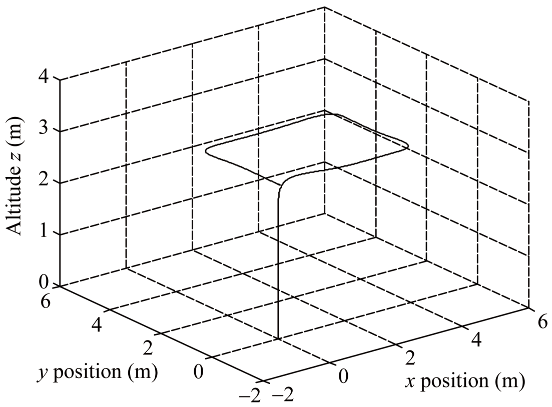


Fig. 5 The horizontal rectangle trajectory tracking result in the second task

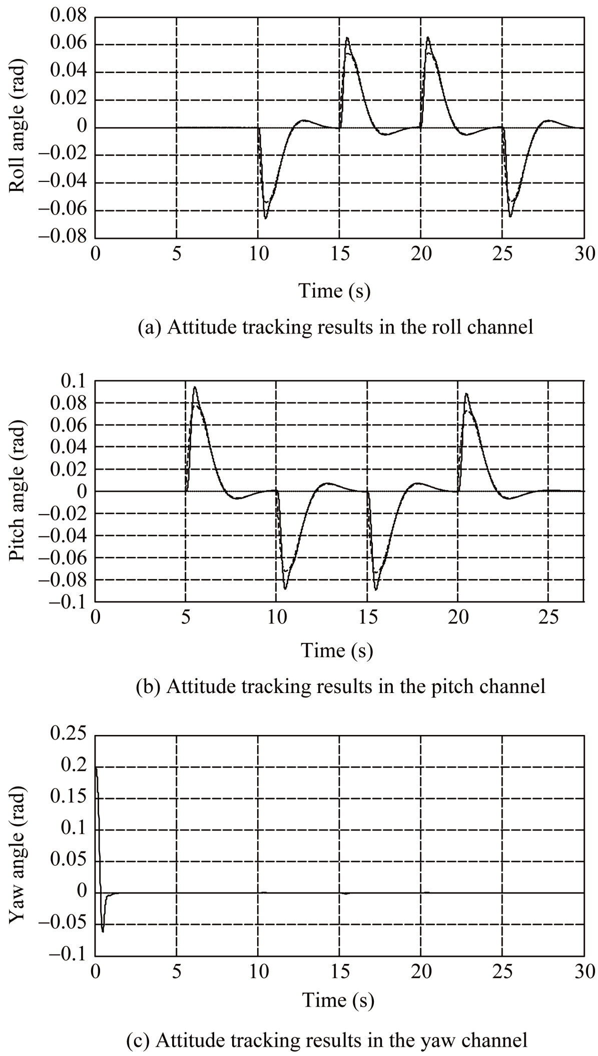


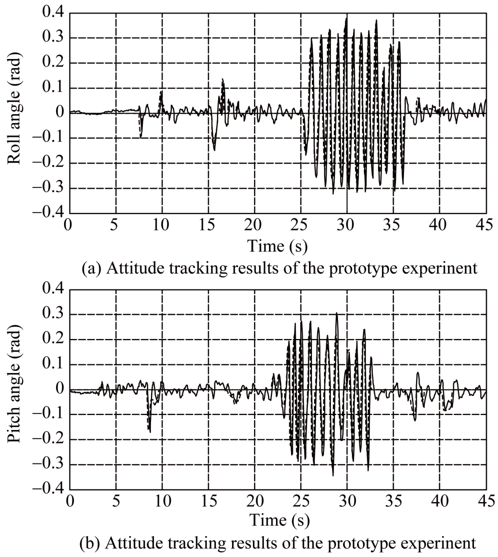
Fig. 6 The tracking performance of the attitude stability controller in the second task with the dashed lines representing the desired attitude commands and the solid lines the actual attitude angles of the aircraft

5 The prototype experiment

Besides the numerical simulation, a prototype experiment is also introduced in this paper to demonstrate the practicability of the designed flight control system. Because the prototype can only carry out remote control flight task at present, only the attitude stability augmentation controller can be tested by the prototype experiment.

In the experiment, the attitude stability augmentation controller sets the prototype to track the imported attitude signals from remote controller automatically. The flying status is shown in Fig. 7. The remote controller commands and the actual attitude states of the prototype are transferred to the upper computer through wireless transmitting module. Fig. 8 depicts the response results in the roll and pitch channels with the dashed lines representing the desired commands and solid lines the actual attitude angles. It illustrates that considering the measurement error caused by the IMU element, the prototype can be regarded as having tracked the desired angles stably.

Fig. 7 The flying status of the prototype experiment



(a) Attitude tracking results of the prototype experiment

(b) Attitude tracking results of the prototype experinent in the pitch channel

Fig. 8 The attitude tracking results of the prototype experiment. The dashed lines represent the attitude commands and the solid lines the measured attitude data

6 Conclusions

In this article, a new trajectory tracking control system for a quad-rotor is proposed. Considering the underactuation, strong coupling properties of the aircraft, a nested double-loops control structure is designed. The adaptive estimation and sliding mode approach are used in the design procedure. And a modification is introduced into the Lyapunov function according to the special structure of the uncertain parameters. The simulation results demonstrate the effectiveness of the proposed control system in the presence of uncertain model parameters and unmodeled disturbance. The prototype experiment result in the last section verifies the practicability of attitude control module of the flight control system.

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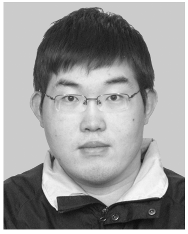

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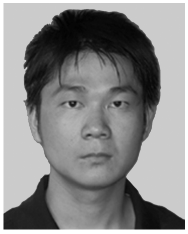

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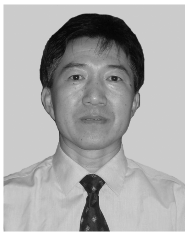

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