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Adaptive control-optimization of a small scale quadrotor helicopter

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1. Introduction

Recently, small scale unmanned aerial vehicles (UAV) have been expected by many fields such as geological exploration, agricultural spraying, atmospheric monitoring, disaster early warning, and target acquisition. For these missions, an autonomous flight control of the copter is indispensable. This autonomous flight control system requires many technologies such as obstacle avoiding as well as attitude and position controlling. The study related to copters controls and usages are now very popular all over the world.

There are many different types of small unmanned copters, such as traditional helicopter, the twin-rotor or tandem-rotor helicopter, the coaxial rotor helicopter and four-rotor helicopter. Although the traditional helicopter, single main rotor or one tail rotor small-scale helicopter, is popular and has been studied widely, yet its characters of complex dynamics and structure, high price and hard to control, instability and easily to crush make it difficult to use by common users. The quadrotor helicopter shares all the merits of the traditional helicopters, such as taking-off and landing vertically, moreover, it has four fixed-pitch rotors mounted at the four ends of a simple cross frame. Owing to the symmetry, this vehicle is dynamically elegant, inexpensive, and simple to design. It is an omni-directional vehicle, and has almost no constraints on its motion. It can be flown in tight spaces and does not require large safety distances to operate. These characteristics make the quadrotor helicopter a good candidate to be utilized in the real life.

There are two methods in modeling the quadrotor helicopter, one is based on Newton-Euler formalism [1, 2], the other is built on the LaGrange method [3, 4]. And the methods in controlling the quadrotor helicopter are proportional-integral-derivative (PID) control [5], fuzzy control [6], back stepping control [7], sliding mode control [8] and adaptive control [9], etc. Among them, the adaptive control has wide application with parameter self-adjusting function and can be used in combination with other control methods.

In reference [10], an adaptive sliding mode controller using input augmentation in order to account for the underactuated property of the helicopter; in reference [11], adaptive fuzzy controller has been designed, using alternate adaptive parameters in the adaptation scheme for quadrotor helicopter robust to wind buffeting; in reference [12], image based visual servoing had been used in the quadrotor control, in which adaptive backstepping control generates input signals for propellers to track the reference velocity accurately even under uncertain effects. But these methods are difficult to achieve, because of still needing accurate mathematical model, or requiring a large amount of the sensor and the observer, or the structure of the controller is still very complex.

In view of the above problems and based on the research in reference [13], the current paper is trying to use Newton-Euler formalism in modeling the quadrotor helicopter; and adaptive control-optimization (ACO) is used in the design of translation and attitude controller in quadrotor helicopter for the first time. The method is simple in algorithm, and the model of control object is less dependent, as well as controller structure is not complicated. Simulation and actual flight test shows that the robustness and real-time is superior to the common adaptive (CA) controller. The method belongs to the author's original research in the application of quadrotor helicopter control, and there is no reference to existing literature.

2. Quadrotor helicopter

Quadrotor helicopter is a kind of non-coaxial multi-rotor flying saucer which can realize vertical takeoff and landing. It is composed of landing gear, base, 2 support frames, four motors and screw propeller , that is shown in Fig. 1.

Fig. 1 The real quadrotor helicopter

Compared with classical helicopter using single main-rotor, its structure is more compact. 2 brackets are orthogonal to each other, 4 rotor symmetrically mounted on the 2 brackets (the distance between 4 rotor and the centre of quadrotor helicopter are same), two front rear rotors on one bracket rotate clockwise (positive pitch) while two rotors on the other orthogonal bracket rotate anticlockwise (reverse pitch), which can be offset against torsional moment and does not need special reaction torque propeller. Besides whatever positive pitch or reverse pitch, the lift is upward, so quadrotor helicopter can produce 4 times as much as the single rotor lift.

3. Quadrotor helicopter dynamics model

In order to achieve the purpose of attitude and position control, this paper establishes the displacement and rotational dynamics model of quadrotor helicopter based on Newton-Euler formalism and rigid body mechanics theory. In order to describe the dynamic model of quadrotor helicopter, two coordinate systems are set up, which are shown in Fig. 2.

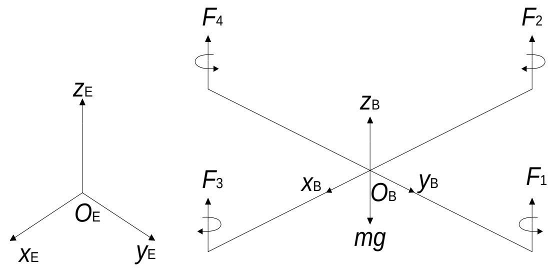


Fig. 2 Earth coordinate system and body coordinate system

3.1. Translation kinematic model

Define $T_\theta, T_\delta, T_\psi$ as the translation matrix of θ, δ, ψ with respect to the body coordinate system. And they can be described as:

$$\left.\begin{aligned} T_\theta &= \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}; \\ T_\delta &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\delta & -\sin\delta \\ 0 & \sin\delta & \cos\delta \end{bmatrix}; \\ T_\psi &= \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}. \end{aligned}\right\} \tag{1}$$

Define the transformation matrix from the body coordinate system to the earth coordinate system as:

$$A_{BE} = T_\theta T_\delta T_\psi . \tag{2}$$

According to Newton-Euler Equation, we can get:

$$\left.\begin{aligned} m\ddot{x}_1 &= f_1; \\ m\ddot{x}_2 &= f_2; \\ m\ddot{x}_3 &= f_3. \end{aligned}\right\}, \tag{3}$$

where m is the mass of model, x_1, x_2, x_3 is the translation in the earth coordinate system, f_1, f_2, f_3 is the three coordinate components of the lift force in the earth coordinate system. Furthermore, there is a relationship as shown:

$$\begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix} = \left(F_1 + F_2 + F_3 + F_4\right) A_{BE} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} - m \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix}. \tag{4}$$

Define F as the sum of F_1, F_2, F_3, F_4 using Eqs. (3) and (4), the translation kinematics and dynamics equation can be described by:

$$\left.\begin{aligned} \ddot{x}_1 &= \frac{\sin\psi\sin\delta + \cos\psi\sin\theta\cos\delta}{m} F; \\ \ddot{x}_2 &= \frac{-\cos\psi\sin\delta + \sin\psi\sin\theta\cos\delta}{m} F; \\ \ddot{x}_3 &= \frac{\cos\theta\cos\delta}{m} F - g. \end{aligned}\right\}. \tag{5}$$

3.2. Rotation kinematic model

Similarly, the angular velocities x_4, x_5, x_6 in the body coordinate system can be described by Euler angels θ, δ, ψ which is shown:

$$\begin{bmatrix} \dot\theta \\ \dot\delta \\ \dot\psi \end{bmatrix} = \begin{bmatrix} \cos\psi\cos\delta & \sin\psi & 0 \\ -\sin\psi\cos\delta & \cos\psi & 0 \\ \sin\delta & 0 & 1 \end{bmatrix}^{-1} \begin{bmatrix} x_4 \\ x_5 \\ x_6 \end{bmatrix}. \tag{6}$$

According to assumptions and Newton-Euler Equation, we can get:

$$\left.\begin{aligned} I_{44}\dot{x}_4 &= l\left(F_4 - F_1\right) + \left(I_{55} - I_{66}\right) x_5 x_6; \\ I_{55}\dot{x}_5 &= l\left(F_2 - F_3\right) + \left(I_{66} - I_{44}\right) x_6 x_4; \\ I_{66}\dot{x}_6 &= \lambda\left(F_1 + F_4 - F_2 - F_3\right) + \left(I_{44} - I_{55}\right) x_4 x_5, \end{aligned}\right\} \tag{7}$$

where l is the distance from the center of the model to the center of any of the rotors (the action point of lift force); λ is a scale factor between yaw torque and the lift force; I_{44}, I_{55}, I_{66} is angular moment with respect to axes in the body coordinate system.

Define M_δ as the control torque of the rotors which generate the roll angle, M_θ as the control torque of the rotors which generate the pitch angle, M_ψ as the yaw angle control torque due to adjusting the rotor speed, which is proportional to the lift force. So there is a matrix U, and:

$$U = \begin{bmatrix} F \\ M_\delta \\ M_\theta \\ M_\psi \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 0 & l & 0 & -l \\ -l & 0 & l & 0 \\ -\lambda & \lambda & -\lambda & \lambda \end{bmatrix} \begin{bmatrix} F_3 \\ F_4 \\ F_2 \\ F_1 \end{bmatrix}. \tag{8}$$

Taking $I_{44} = I_{55}$ into consideration, using Eqs. (6), (7) and (8), the rotation dynamic equations of the quadrotor helicopter can be described:

$$\left.\begin{aligned}\dot{x}_4 &= \frac{M_\delta + (I_{55} - I_{66})x_5x_6}{I_{44}};\\ \dot{x}_5 &= \frac{M_\theta + (I_{66} - I_{44})x_6x_4}{I_{55}};\\ \dot{x}_6 &= \frac{M_\psi}{I_{66}}.\end{aligned}\right\} \quad (9)$$

3.3. Rotor lift model

This paper use the lift test experiment and MATLAB numerical fitting method for obtaining the numerical relationship between the input signal and lift, and it obtained good application effect.

Do secondary fitting on the curve by MATLAB, we can get:

$$PWM = 1105 - 260 \times F_t + 22.23 \times F_t^2, \quad (10)$$

where PWM is the input signal which the positive pulse width is 1–2 ms, F_t is the lift generated by rotors. With above equation, it can be easily to get the rotor lift value through *PWM*.

4. ACO controller

4.1. Kernel algorithm of the controller

This paper introduces a kind of adaptive optimal control method, which is used to control the translation and attitude of quadrotor helicopter. The control theory about the controller is deduced as follows.

Supposing a controlled system in Eq. (11):

$$y(n) = W \times x(n), \quad (11)$$

where $x(n)$ is the state of the system, $y(n)$ is the output of the system, W is the weighted coefficient.

Supposing the error between the desired state $x_{dk}(n)$ and the output $y_k(n)$ is $e_k(n)$ in Eq. (12):

$$e_k(n) = x_{dk}(n) - y_k(n), \quad (12)$$

where k is the number of samples.

Define $\hat{\nabla}_k$ as the error gradient estimate of the system, where:

$$\hat{\nabla}_k = \nabla\left[e_k^2\right] = 2e_k \nabla\left[e_k\right]. \quad (13)$$

According to Eqs. (11) and (12), we can get:

$$\nabla\left[e_k\right] = -x_k. \quad (14)$$

So the error gradient estimate of the system can be obtained:

$$\hat{\nabla}_k = -2e_k x_k \quad (15)$$

and

$$W_{k+1} = W_k - \mu \hat{\nabla}_k, \quad (16)$$

where μ is the variable of algorithms.

According to Eqs (15) and (16), we can get:

$$W_{k+1} = W_k + 2m e_k x_k. \quad (17)$$

By W_0 and x_0, we can obtain W_1. Followed by analogy, W_m can be obtained and $y_m(n)$ can be calculated finally:

$$y_m(n) = W_m \times x_m(n), \quad (18)$$

where $m = 1, 2, 3, \ldots k+1, \ldots$.

Based on the control theory above, we can get the structure of adaptive optimal controller, which is shown in Fig. 3. Compared on simulation and actual flight experiments (section 5), we can get that its performance is superior to the adaptive controller designed by traditional method.

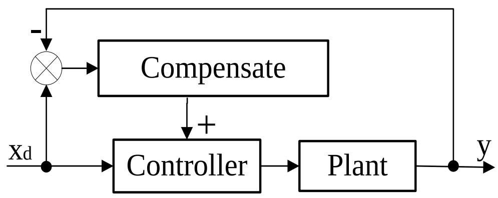


Fig. 3 The structure of the kernel controller

4.2. Controller design

There are four indirect control input F, M_δ, M_θ, M_ψ, and six outputs: three translation positions and three angle attitudes in quadrotor helicopter. Although the system is an under-actuated system, it can realize controllable completely by using a few input signals to control the majority of output variables (decoupling method), and the channel control structure completing the function is shown in Fig. 4. Where the inputs are the x_{id}, i = 3, 4, 5, 6, δ_d, θ_d, ψ_d. The feedback achieved by sensors are x_i, $i = 3, 4, 5, 6$ and δ, θ, ψ. Specific design is described as follows.

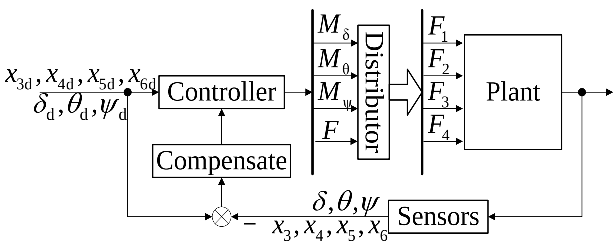


Fig. 4 The channel controller structure

4.2.1. Translation controller

With Eqs. (3), (4), and (5), the Eq. (19) can be expressed with the pseudo-control variables $\tau_{1,2,3}$:

$$\left.\begin{aligned} \ddot{x}_1 &= \tau_1; \\ \ddot{x}_2 &= \tau_2; \\ \ddot{x}_3 &= \tau_3, \end{aligned}\right\} \tag{19}$$

where τ_1, τ_2, τ_3 corresponding expectations are τ_{1d}, τ_{2d}, τ_{3d}. According to section 4.1, suppose $\tau_{kd} = d_k(n)$, $e_k = d_k - y_k = t_{kd} - W_k \times F_k$, then:

$$\begin{bmatrix} \tau_{1dk} \\ \tau_{2dk} \\ \tau_{3dk} + g \end{bmatrix} = M \times F_{dk}, \tag{20}$$

where M is:

$$M = \begin{bmatrix} \frac{sin\psi\, sin\delta + cos\psi\, sin\theta\, cos\delta}{m} & 0 & 0 \\ 0 & \frac{-cos\psi\, sin\delta + sin\psi\, sin\theta\, cos\delta}{m} & 0 \\ 0 & 0 & \frac{cos\theta\, cos\delta}{m} \end{bmatrix}$$

Solve (20) by ACO method (13)~(18), we can get:

$$\begin{bmatrix} \tau_{1m} \\ \tau_{2m} \\ \tau_{3m} + g \end{bmatrix} = W_m \times F_m. \tag{21}$$

Supposing $[\theta_0, \delta_0, \psi_0]^T = [0,0,0]^T$, $m = 1$, then $W_0 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{cos\theta\, cos\delta}{m} \end{bmatrix}$, W_m and $\tau_{1m,2m,3m}$ can be obtained by selecting suitable parameters for iterative. Among them, m is iteration times.

4.2.2. Rotation controller

Supposing:

$$\left.\begin{aligned} \dot{\theta} &= \tau_4; \\ \dot{\delta} &= \tau_5; \\ \dot{\psi} &= \tau_6, \end{aligned}\right\} \tag{22}$$

according to Eq. (6), we can get:

$$\begin{bmatrix} \tau_4 \\ \tau_5 \\ \tau_6 \end{bmatrix} = N \begin{bmatrix} x_4 \\ x_5 \\ x_6 \end{bmatrix}, \tag{23}$$

where $N = \begin{bmatrix} cos\psi\, cos\delta & sin\psi & 0 \\ -sin\psi\, cos\delta & cos\psi & 0 \\ sin\delta & 0 & 1 \end{bmatrix}^{-1}$.

According to section 4.1, we can get:

$$\begin{bmatrix} \tau_{4dk} \\ \tau_{5dk} \\ \tau_{6dk} \end{bmatrix} = N \times \begin{bmatrix} x_{4dk} \\ x_{5dk} \\ x_{6dk} \end{bmatrix}. \tag{24}$$

According to ACO method (13)~(18), we can get:

$$\begin{bmatrix} \tau_{4n} \\ \tau_{5n} \\ \tau_{6n} \end{bmatrix} = W_n \times \begin{bmatrix} x_{4n} \\ x_{5n} \\ x_{6n} \end{bmatrix}, \tag{25}$$

where x_4, x_5, x_6 can be acquired by sensors, μ, W_n and $\tau_{4n,5n,6n}$ can be achieved by iteration with suitable control parameter μ. Among them n is iteration time.

4.2.3. Channel distributor controller

With the Eq. (10), we can get:

$$F_i = \frac{261 + \sqrt{88.92 PWM_i - 30135.6}}{44.46}, \tag{26}$$

where $i = 1,2,3,4$.

With the Eq. (8), we can get:

$$\left.\begin{aligned} F &= F_1 + F_2 + F_3 + F_4; \\ M_\delta &= (F_4 - F_1) \times l; \\ M_\theta &= (F_2 - F_3) \times l; \\ M_\psi &= \lambda(F_1 + F_4 - F_2 - F_3). \end{aligned}\right\} \tag{27}$$

While $l = 0.24m$, suppose $\lambda = 2.703 \times 10^{-2}$,and we can get the values of F, M_δ, M_θ, M_ψ by solving (26) and (27).

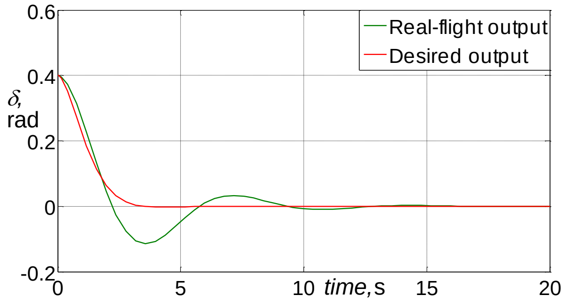
5. Simulation

As ACO controller has been discussed in the fourth section, and in order to verify its advantages to CA controller, this section uses Matlab-simulink to simulate and compare this two control methods. The initial state of attitude angle (δ, ψ, θ) in quadrotor helicopter are (0.4 rad, 0.4 rad, 0.5 rad), the desired steady-state value are(0, 0, 0), and it is given a drop signal at 6s and returned to 0 at 10 s. The initial state of (x, y, z) are (0, 0, 0), in which the expected translation at x, y axis direction are 1 m; at z axis direction, its translation stays in 3m for a period of time, and then drop down to the steady state value 2 m. Simulation parameters of ACO controller are shown in Table. Comparison of simulation results between ACO controller and CA controller is shown in Figs. 5 and 6.

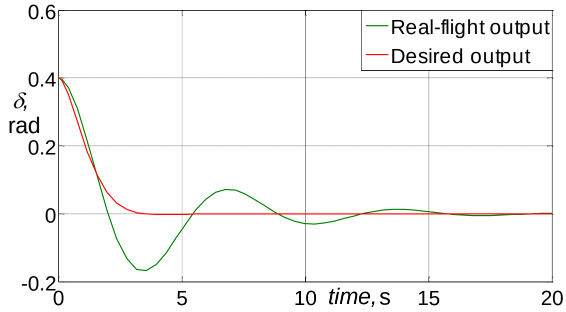
Table

The controller parameters in simulation

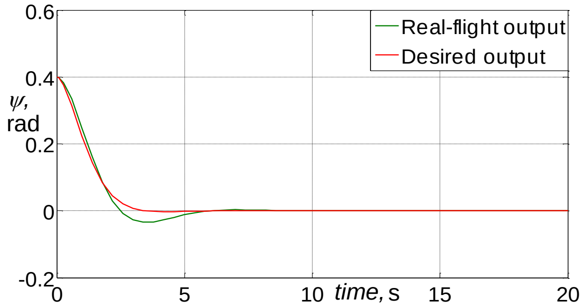
W_0	μ	δ_0, rad	ψ_0, rad	θ_0, rad	x_0, m	y_0, m	z_0, m
$\boldsymbol{0}_{3\times3}$	0.001	0.4	0.4	0.5	0	0	0



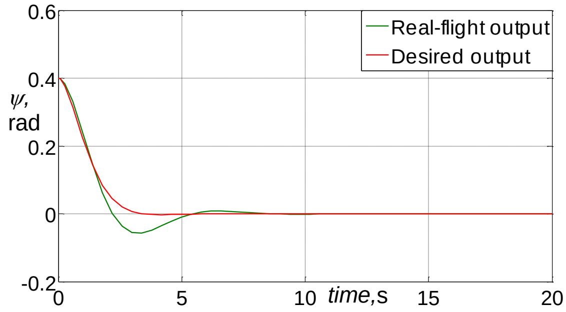
a) Roll tracking process with CA controller



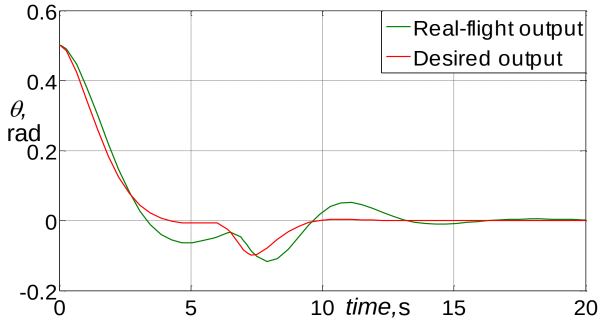
b) Roll tracking process with UCA controller



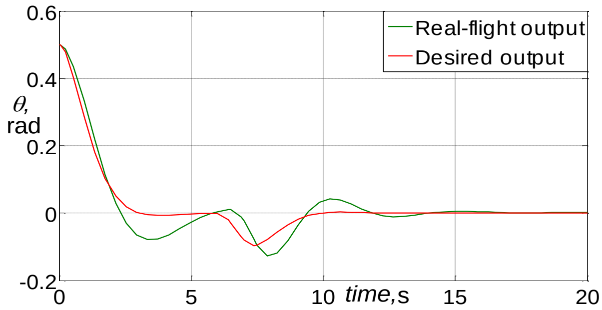
c) Yaw tracking process with CA controllerd



d) Yaw tracking process with UCA controller



e) Pitch tracking process with CA controller

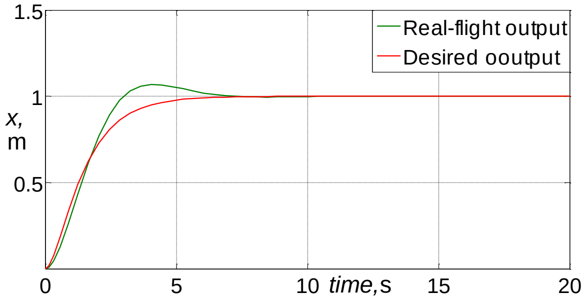


f) Pitch tracking process with UCA controller

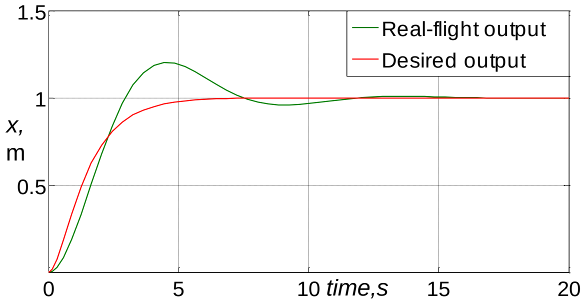
Fig. 5 The comparison of angle control results between ACO controller and CA controller

Fig. 5 shows the comparison results of attitude angle simulation between two controllers, as can be seen from the graph, as to roll angle, the overshoot of ACO controller is only half of that of CA controller, and adjusting time is 5 s less than CA controller; as to yaw, the overshoot of ACO controller is about half of that of CA controller, and adjusting time is 3 s less than CA controller; as to pitch angle, the overshoot of ACO controller is about 2/3 of that of CA controller, and adjusting time is 1s less than CA controller. Therefore, either overshoot or adjust the time from the attitude control, the ACO controller is dominant.

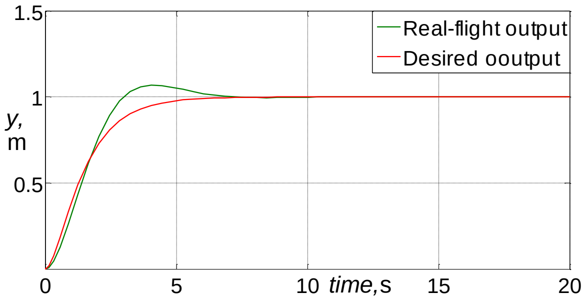
Fig. 6 shows the comparison results of translation simulation between two controllers, as can be seen from the graph, as to translation at direction of x axis and y axis, the overshoot of ACO controller is about 1/3 of that of CA controller, and adjusting time is 4s less than CA controller ; as to translation at direction of z axis, the overshoot of ACO controller is about half of that of CA controller, and adjusting time is 4 s less than CA controller. Therefore, either overshoot or adjust the time from the translation control, the ACO controller is dominant and has better robustness.



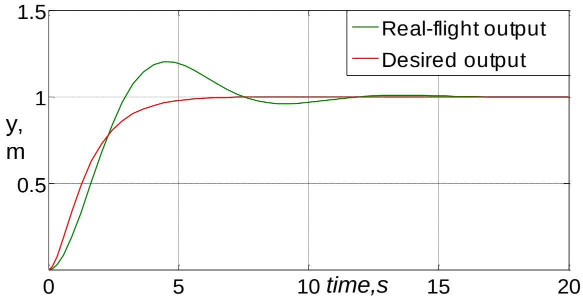
a) X tracking process with CA controller



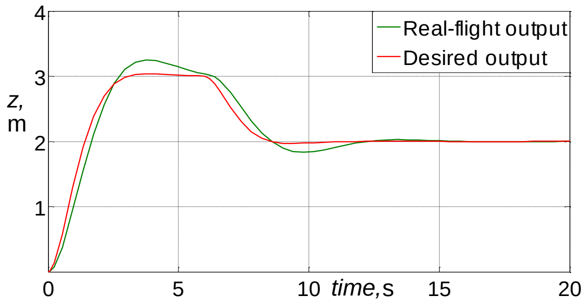
b) X tracking process with UCA controller



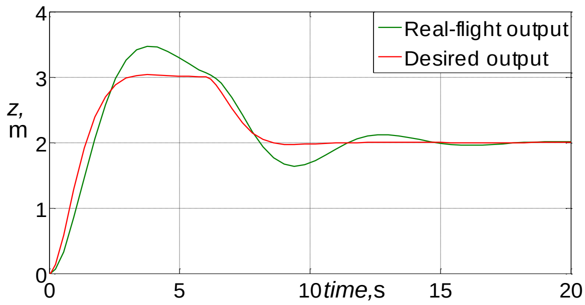
c) Y tracking process with CA controller



d) Y tracking process with UCA controller



e) Z tracking process with ACO controller



f) Z tracking process with CA controller

Fig. 6 The comparison of the translation control results between ACO controller and CA controller

6. Experiment analysis

Hardware system of quadrotor helicopter is designed and built to test and further validate the reliability of simulation results in this section. The hardware system consists of power unit, an inertial measurement unit (IMU), airborne navigation positioning unit, wireless communication unit, height measuring device, the rotor speed measuring unit and embedded micro controller unit (ARM). Two experiments are done to analyze and compare actual control effect of ACO and CA controller in this section.

Hovering control experiment is done to compare the actual attitude control effect of two controllers, let quadrotor helicopter vertical rise from (0, 0,0) in the body coordinate system, then hover at (0, 0, 1.5 m) in the earth coordinate system. Crosswind of about level 4 (moderate breeze) is pulsed on the quadrotor helicopter all the time (common disturbance in actual flight). When quadrotor helicopter is controlled by ACO control, system can return the balance state in 5 s; and by CA control, it would take 8-9 s at least for recovery.

The flight tracking line of "8" shape is designed in translation control experiment. Beginning from (0, 0, 0.6 m) in the earth coordinate system, the flying curve followed by (0.6 m, 0.6 m, 0.6 m), (0, 1.2 m, 0.6 m), (-0.6 m, 1.8 m, 0.6 m), (0, 2.4 m, 0.6 m), (0.6 m, 1.8 m, 0.6 m), (0, 1.2 m, 0.6 m), (-0.6 m, 0.6 m, 0.6 m),and finally back to (0, 0, 0.6 m).

Fig. 7 The real-flight hovering experiment scene

Fig. 8 Fly tracking route of "8" shape

The hovering and "8" shape flight tracking route of quadrotor helicopter are shown as Figs. 7 and 8.

There are certain steady-state errors of angle and translation caused by the sensor noise in the experiment, and in addition, there are many other unavoidable factors generating steady-state error, just like vibration on the body produced by the rotation of four rotor motors, communication and control delay. But despite these interferences, ACO control method can limit the steady-state error in a small range, the overshoot at every turning point is small, the regulating time returning to the "8" line is short, flight path is stable and smooth, fitting of the tracking line and controller robustness are better. The overshoot of CA control method at every turning point is larger, the regulating time returning to the "8" line is longer, flight path is not so smooth, fitting of the tracking line and controller robustness are worse than that of ACO.

7. Conclusions

This paper establishes the kinematics model of quadrotor helicopter by Newton Euler method, and obtains rotor lift model through experiment. For the first time attitude and displacement control of quadrotor helicopter is achieved by ACO method in practical systems. Results of simulation and experiment show that ACO method can meet the stability and rapidity requirement of quadrotor helicopter control and has better robustness and real-time performance. In the follow-up work, the improved ACO control method will be used to reduce the steady-state error further and realize stabile control on attitude and translation of quadrotor helicopter.

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MAŽŲ MATMENŲ KETURIŲ ROTORIŲ SRAIGTASPARNIO ADAPTYVIOJO VALDYMO OPTIMIZAVIMAS

R e z i u m ė

Šis straipsnis yra skirtas mažo keturių rotorių sraigtasparnio stabilumo ir skrydžio valdymo problemai spręsti. Keturių rotorių sraigtasparnio dinaminis modelis sukurtas remiantis Niutono ir Oilerio lygtimis ir kietojo kūno teorija, o keliamosios jėgos ir valdymo signalo tarpusavio ryšys yra sudarytas antriniu priderinimu. Adaptyviojo valdymo optimizavimo (AVO) metodas valdymo sistemai yra taikomas pirmą kartą ir užtikrina keturių rotorių sraigtasparnio padėties ore stabilumą ir judėjimo valdymą. Modeliavimo ir skrydžio eksperimento realiu laiku rezultatai rodo, kad adaptyviojo valdymo optimizavimo (AVO) metodas užtikrina didesnį stabilumą ore ir geresnį valdomumą realiu laiku, palyginti su bendraisiais adaptyviojo valdymo metodais.

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ADAPTIVE CONTROL-OPTIMIZATION OF A SMALL SCALE QUADROTOR HELICOPTER

S u m m a r y

A new method is proposed in this paper in view of the problem of stability and translation tracking control of small scale quadrotor helicopter. The dynamic model of quadrotor helicopter is established based on Newton Euler equation and rigid body theory, and model of the relationship between lift and input control signal is established by secondary fitting. The adaptive control-optimization (ACO) method is applied to the control system for the first time, and it has realized the attitude stability and translation tracking control of quadrotor helicopter. Results of simulation and real-flight experiment show that adaptive control-optimization (ACO) method has better robustness and real-time performance on attitude and translation control in comparison with common adaptive control methods.

Keywords: quadrotor helicopter, adaptive control-optimization (ACO), modeling, simulation, real-flight experiment.

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