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A novel control scheme for quadrotor UAV based upon active disturbance rejection control

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A B S T R A C T

A double closed-loop active disturbance rejection control (ADRC) scheme is proposed to deal with some difficult control problems in the quadrotor unmanned aerial vehicle (UAV) system such as nonlinearity, strong coupling and sensitive to disturbance, etc. Firstly, the virtual control variables are introduced to decouple the quadrotor flight system that can simplify the mathematical model of the system. Secondly, the extended state observer (ESO) is used to estimate and compensate the internal uncertainties and external disturbances in real time which can improve the robustness and anti-disturbance ability of the system. Finally, the stability of the system is proved. The simulation results show that the control scheme proposed in this paper can ensure that the quadrotor track the target trajectory quickly and accurately while maintaining stability, even with external disturbances.

1. Introduction

In recent years, the quadrotor unmanned aerial vehicle has been widely applied in both civil and military fields. Now, many kinds of difficult and dangerous missions can be achieved by quadrotor, such as research, succour, inspection, surveillance, aerial photography, etc.

Because of its simple structure, low energy consumption, easy operation, free hover, vertical take off and landing, the quadrotor has received extensive attention and deep research from the experts and scholars around the world. The quadrotor has six degrees of freedom, including three position outputs and three attitude angle outputs, however, there are only four control inputs, so it is a typical under-actuated system. The quadrotor system has some characteristics, multivariables, nonlinearity, strong coupling, sensitive to disturbance, which make it difficult to design the controller for trajectory tracking. At present, many control methods have been used for the quadrotor UAV. In [1–3], adaptive controller is proposed for controlling the quadrotor. Backstepping and sliding mode control have been applied in quadrotor UAV are presented in [4–7]. In [8], fuzzy neural networks controller is designed for the quadrotor in terms of its control efforts and tracking accuracy. In [9,10], predictive control scheme is proposed to cope with the trajectory tracking problem for UAV, and a nonlinear controller for the quadrotor is proposed in [11] using neural networks. But these methods either rely on precise mathematical models or require knowledge of the upper bounds of uncertainties, which are easily influenced by internal uncertainties and unknown disturbances.

Active disturbance rejection control technique [12,13] is a new control strategy emerged in the 80s of last century. ADRC consists of three parts: tracking differentiator (TD), ESO [14–16] and state error feedback control law. The purpose of designing a TD is to arrange a transition process for the input, and obtain a smooth input signal to reduce the initial error of the system. The ESO is the core of the whole system, which can estimate the total disturbance include internal unknown and external disturbances, and then the total disturbance will be compensated by state error feedback control law. ADRC is a control method that does not depend on accurate system model, it has fast tracking speed, high control precision and strong anti-disturbance ability, it has been widely used in many theoretical researches, experiments and engineering applications. Therefore, ADRC will be used to design the control system of the quadrotor UAV in this paper.

In this paper, ADRC not only is adopted in attitude loop, but also adopted in position loop, it is a novel control scheme which called double closed-loop active disturbance rejection control. In order to simplify the mathematical model of the system, the virtual control variables are introduced to decouple the quadrotor flight system, and the expressions of yaw angle and pitch angle can be calculated through the system model and the virtual control variables, then applied to the cascade control system. The extended state observer is used to estimate and compensate the

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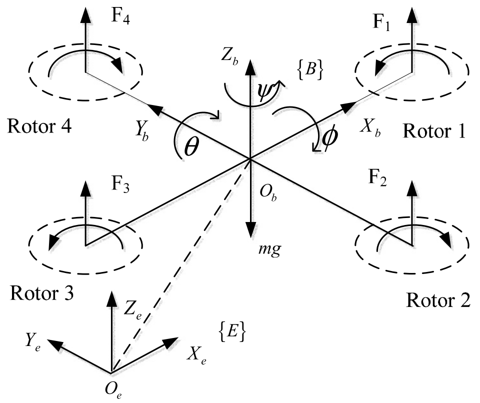

Fig. 1. Free-body diagram of the quadrotor.

total disturbances in real time which can improve the robustness and anti-disturbance property of the system without the knowledge of the system uncertainty in advance. The stability of the system is proved, which can guarantee the position and attitude tracking performance of the quadrotor UAV.

This paper is organized as follows: A typical quadrotor model is introduced in Section 2. An ADRC based control scheme for quadrotor UAV is designed in Section 3. Stability of the system is proved in Section 4. Results of simulation experiments are illustrated in Section 5. Finally, some concluding remarks are given in Section 6.

2. System modelling

The quadrotor has six degrees of freedom, including three position variables and three attitude angle variables. Because of its special characteristics, under-actuated, strong coupling and sensitive to disturbance, it is very difficult to establish its dynamical model accurately. In order to establish the model of the quadrotor, the fixed frame $\{E\}$ and body frame $\{B\}$ must be established firstly [17,18], the lift force analysis diagram is shown in Fig. 1. As can be seen from Fig. 1 that the quadrotor is mainly affected by the lift forces of four rotors (F_1, F_2, F_3, F_4) and its own gravity, each rotor's lift force is proportional to the rotor speed squared, then the position control and the attitude control of the quadrotor can be achieved by the rotor's speed voltage.

The flight states of the quadrotor consist of three position coordinates (x, y, z) and three attitude angles (θ, ϕ, ψ), θ, ϕ and ψ represent pitch angle, roll angle and yaw angle respectively. The position coordinates can determine the relative location between the quadrotor body frame $\{B\}$ and the fixed frame $\{E\}$, attitude angles can determine the flight attitude of the quadrotor. Let $R_{EB}(\theta, \phi, \psi)$ denote the transformation matrix between fixed frame $\{E\}$ and body frame $\{B\}$ that using Euler–Lagrange formulation, which can be expressed as

$$R_{EB}(\theta, \phi, \psi) = \begin{bmatrix} R_1 & R_2 & R_3 \end{bmatrix} \tag{1}$$

where

$$R_1 = \begin{bmatrix} \cos\psi\cos\theta \\ \sin\psi\cos\theta \\ -\sin\theta \end{bmatrix}$$

$$R_2 = \begin{bmatrix} \cos\psi\sin\phi\sin\theta - \sin\psi\sin\phi \\ \sin\psi\sin\phi\sin\theta + \cos\psi\cos\phi \\ \cos\theta\sin\phi \end{bmatrix}$$

$$R_3 = \begin{bmatrix} \cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi \\ \sin\psi\sin\theta\cos\phi - \sin\phi\cos\psi \\ \cos\theta\cos\phi \end{bmatrix}$$

Table 1
System parameters of the quadrotor UAV.

Symbol	Physical meaning	Value	Unit
m	Quality of the quadrotor	2	kg
l	Length between the centre of the aircraft and the rotor	0.35	m
k_c	Torque coefficient	0.035	m
k_f	Coefficient of air resistance	0.012	$\mathrm{N\,s^2/rad^2}$
I_1	Rotational inertia of the x-axis	1.25	$\mathrm{kg\,m^2}$
I_2	Rotational inertia of the y-axis	1.25	$\mathrm{kg\,m^2}$
I_3	Rotational inertia of the z-axis	2.5	$\mathrm{kg\,m^2}$
g	Gravitational acceleration	9.8	$\mathrm{m/s^2}$

according to the lift force analysis from Fig. 1, the lift forces of the quadrotor in the body frame $\{B\}$ can be expressed as

$$F_B = \begin{bmatrix} F_{x_B} \\ F_{y_B} \\ F_{z_B} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ F_1 + F_2 + F_3 + F_4 \end{bmatrix} \tag{2}$$

from equations (1) and (2), the lift forces of the quadrotor in the fixed frame $\{E\}$ can be calculated by

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = R_{EB} \cdot F_B = \left(\sum_{i=1}^{4} F_i \right) \begin{bmatrix} \cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi \\ \sin\psi\sin\theta\cos\phi - \sin\phi\cos\psi \\ \cos\theta\cos\phi \end{bmatrix}$$

then, the translational movement of the quadrotor can be written as

$$\begin{cases} \ddot{x} = (F_x - k_f\dot{x})/m \\ \ddot{y} = (F_y - k_f\dot{y})/m \\ \ddot{z} = (F_z - mg - k_f\dot{z})/m \end{cases} \tag{3}$$

and also the rotational movement of the quadrotor can be expressed as

$$\begin{cases} \ddot{\theta} = l(-F_1 + F_2 + F_3 - F_4 - k_f\dot{\theta})/I_2 + (I_3 - I_1)\dot{\phi}\dot{\psi}/I_2 \\ \ddot{\phi} = l(-F_1 - F_2 + F_3 + F_4 - k_f\dot{\phi})/I_1 + (I_2 - I_3)\dot{\theta}\dot{\psi}/I_1 \\ \ddot{\psi} = [k_c(-F_1 + F_2 - F_3 + F_4) - k_f\dot{\psi}]/I_3 + (I_1 - I_2)\dot{\theta}\dot{\phi}/I_3 \end{cases} \tag{4}$$

Combining the equations (3) and (4), the mathematical model [19–22] of the quadrotor UAV flight system can be represented as

$$\begin{cases} \ddot{x} = (F_x - k_f\dot{x})/m \\ \ddot{y} = (F_y - k_f\dot{y})/m \\ \ddot{z} = (F_z - mg - k_f\dot{z})/m \\ \ddot{\theta} = l(-F_1 + F_2 + F_3 - F_4 - k_f\dot{\theta})/I_2 + (I_3 - I_1)\dot{\phi}\dot{\psi}/I_2 \\ \ddot{\phi} = l(-F_1 - F_2 + F_3 + F_4 - k_f\dot{\phi})/I_1 + (I_2 - I_3)\dot{\theta}\dot{\psi}/I_1 \\ \ddot{\psi} = [k_c(-F_1 + F_2 - F_3 + F_4) - k_f\dot{\psi}]/I_3 + (I_1 - I_2)\dot{\theta}\dot{\phi}/I_3 \end{cases} \tag{5}$$

where x, y, z are the positions of the quadrotor, θ is the pitch angle, ϕ is the roll angle and ψ is the yaw angle, F_1, F_3, F_2, F_4 are the lift forces of the four rotors respectively, and other system parameters are shown in Table 1.

In order to simplify the design procedures and the presentation of the quadrotor flight system, the virtual control variables of the whole system U_1, U_2, U_3, U_4 are introduced to transform with the lift forces F_1, F_2, F_3, F_4, the variable transformation formula can be expressed as formula (6), and U_x, U_y, U_z as the virtual control inputs in the position loop, which is given by the formula (7)

$$\begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{bmatrix} = \begin{bmatrix} \frac{1}{m} & \frac{1}{m} & \frac{1}{m} & \frac{1}{m} \\ -\frac{l}{I_2} & \frac{l}{I_2} & \frac{l}{I_2} & -\frac{l}{I_2} \\ -\frac{l}{I_1} & -\frac{l}{I_1} & \frac{l}{I_1} & \frac{l}{I_1} \\ -\frac{k_c}{I_3} & \frac{k_c}{I_3} & -\frac{k_c}{I_3} & \frac{k_c}{I_3} \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix} \tag{6}$$

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