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Attitude Decoupling Control for Quadrotor Aircraft Based on Linear Active Disturbance Rejection Control Technique

To cite this article: Sajjun Zhou *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **569** 042034

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Attitude Decoupling Control for Quadrotor Aircraft Based on Linear Active Disturbance Rejection Control Technique

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Abstract. An attitude decoupling controller based on linear active disturbance rejection control (LADRC) is designed for small quadrotor aircraft, considering the problems existing in the controller based on active disturbance rejection control (ADRC), such as complicated design and parameters tuning difficulties in project implementation. First, the nonlinear and couple model of small quadrotor aircraft were established, and the LADRC was introduced, which described the principles of the ability of decoupling rejection control for multiple-input and multiple-output (MIMO) system and tuning method, then the model was decoupled. After that, the attitude controller based on second-order LADRC is designed and parameters is turned according to the desired settling time. Finally, the simulation test of the design was carried out. The simulation results indicate that the designed controller has strong robustness and anti-disturbance performance, and does not have accurate models. Moreover, there is only one parameter needs tuning in this controller, which makes the design easy to be realized and shows great engineering value.

1. Introduction

According to its vertical research[1], the small quadrotor is a take-off and landing, aerial suspension typical multi-variable, nonlinear, strongly coupled under actuated system[2]. In recent years, researchers have focused on the lots of four-rotor works been done on aircraft modelling, control, and engineering applications for quadrotors[3-8]. At present, the main research directions of the flight control system are the design and engineering application.

Attitude control is the foundation and key of the entire flight control system[9]. Modern control theory has been widely used in the design of four-rotor flight control systems, such as sliding mode control[10], adaptive control[5, 11], nonlinear control[12], etc., but these control methods are complex in design. And in practice, there are restrictions in the application. However, due to the limitations of its own structure, the traditional PID controller often needs to make trade-offs between dynamic performance and steady-state performance[13]. The Active Disturbance Rejection Control (ADRC)[14] proposed by researcher Han Jingqing enriches the essence of PID control on the basis of absorbing the achievements of modern control theory. it has the advantages of low model accuracy, short adjustment time, small overshoot, strong robustness and other advantages. Currently, ADRC has achieved good control[9, 15-17] in the design of the four-rotor aircraft control system. In 2006, Gao Zhiqiang[18] proposed Linear Active Disturbance Rejection (LADRC), of which the bandwidth-based parameter tuning method greatly simplifies the tuning process and advances the application of ADRC in engineering.

In this paper, based on the nonlinear model of the attitude of the four-rotor aircraft, a method based on LADRC four-rotor attitude decoupling control was proposed. Firstly, the nonlinear coupling model



of the attitude of the four-rotor aircraft was established. Then, the decoupled controller design of the established model was introduced by LADRC, and the controller parameters were adjusted based on the requirements of transition time in the attitude control. Finally, the robustness and immunity of the proposed control method were simulated and analysed.

2. Small quadrotor attitude model

According to the literature [4], the attitude dynamics model of a quadrotor is:

$$\begin{cases} \dot{\phi} = p + (q \sin \phi + r \cos \phi) \tan \theta \\ \dot{\theta} = q \cos \phi + r \sin \phi \\ \dot{\psi} = (q \sin \phi + r \cos \phi) \sec \theta \\ \dot{p} = \frac{1}{I_x} [lU_1 + qr(I_y - I_z)] \\ \dot{q} = \frac{1}{I_y} [lU_2 + pr(I_z - I_x)] \\ \dot{r} = \frac{1}{I_z} [U_3 + pq(I_x - I_y)] \end{cases} \quad (1)$$

Where ϕ, θ, ψ is the roll angle, pitch angle and yaw angle of the aircraft respectively; p, q, r are the components of the body's angular velocity on the three coordinate axes ox, oy, oz in the body coordinate system; l is the distance which the centroid of the aircraft to the centroid of the rotor. And $U_i (i=1,2,3)$ is the input of the roll moment, pitch and yaw control for the three axes of inertia I_x, I_y, I_z in the body coordinate.

The relationship between the input $U_i (i=1,2,3)$ quantity and the motor speed of the aircraft, ω_i , could be expressed as:

$$\begin{bmatrix} U_1 \\ U_2 \\ U_3 \end{bmatrix} = \begin{bmatrix} 0 & k_b & 0 & -k_b \\ -k_b & 0 & k_b & 0 \\ k_d & -k_d & k_d & -k_d \end{bmatrix} \begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix} \quad (2)$$

In this formula, k_b is the lift coefficient and k_d is the drag coefficient. The relationship between the angular velocity of the Euler angle and the angular velocity of the body is

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 & -\sin \theta \\ 0 & \cos \phi & \sin \phi \cos \theta \\ 0 & -\sin \phi & \cos \phi \cos \theta \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \quad (3)$$

Coupling characteristic band of attitude dynamics model of quadrotor the difficulty of designing the flight control law, the design of the model is often used in general linearization to reduce design difficulty [4-5].

Although this method simplifies the design of the control law, it also reduces the manoeuvrability of the quadrotor in response to complex environments.

3. Attitude decoupling control method

3.1. LADRC structure

Taking the Second order time-invariant systems as an example, the designed LADRC structure is shown in Fig.1[19]

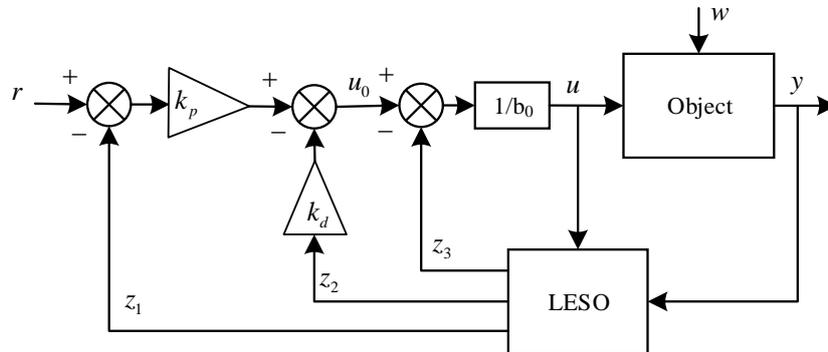


Fig.1 LADRC structure

Where y and u correspond to the input and output of the system respectively; r is the reference input; b_0 is the estimated value of system parameter, b is unknown; ω is the external disturbance $k_p = \omega_c^2$, $k_d = 2\omega_c$, ω_c is the controller bandwidth; $z = [z_1, z_2, z_3]^T$ is the state matrix of the Linear. The system state $z = [x_1, x_2]^T$ is set, and the total disturbance (system internal disturbance, external disturbance) is goblet $f(\cdot)$, and $f(\cdot)$ could be micro and bounded, the following form LESO could estimate $f(\cdot)$:

$$\begin{cases} \dot{z} = Az + Bu + L(y - \hat{y}) \\ \hat{y} = Cz \end{cases} \quad (4)$$

Among them, $A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}$, $B = \begin{bmatrix} 0 \\ b_0 \\ 0 \end{bmatrix}$, $C = [1 \ 0 \ 0]$, $L = [\beta_1, \beta_2, \beta_3]^T$, L is the observer gain

Value of β_i ($i = 1, 2, 3$) is related to the observer bandwidth ω_0 , and ω_0 could be adjusted appropriately.

$$z_1 \rightarrow x_1, z_2 \rightarrow x_2, z_3 \rightarrow f(\cdot)$$

In summary, the LADRC for the design of the second-order steady system could be expressed as:

$$\begin{cases} e = y - z_1 \\ \dot{z}_1 = z_2 + \beta_1 e \\ \dot{z}_2 = z_3 + \beta_2 e + b_0 u \\ \dot{z}_3 = \beta_3 e \\ u_0 = k_p(r - z_1) - k_d z_2 \\ u = \frac{u_0 - z_3}{b_0} \end{cases} \quad (5)$$

3.2. Four-rotor attitude decoupling control method based on LADRC.

Introducing control and external disturbance, then further derive the formula (1), and the Euler angle dynamic model including the external disturbance is [9]:

$$\begin{bmatrix} \ddot{\varphi} \\ \ddot{\theta} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} f_1(\varphi, \dot{\varphi}, \theta, \dot{\theta}, \psi, \dot{\psi}) + w_1(t) \\ f_2(\varphi, \dot{\varphi}, \theta, \dot{\theta}, \psi, \dot{\psi}) + w_2(t) \\ f_3(\varphi, \dot{\varphi}, \theta, \dot{\theta}, \psi, \dot{\psi}) + w_3(t) \end{bmatrix} + \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \quad (6)$$

Among them:

$$V = [V_1, V_2, V_3]^T = B(\phi, \psi, t)[U_1, U_2, U_3]^T \tag{7}$$

$$B(\phi, \theta, \psi, t) = \begin{bmatrix} 1 & \sin \phi \tan \theta & \cos \phi \tan \theta \\ 0 & \cos \phi & \sin \phi \\ 0 & \sin \phi \sec \theta & \cos \phi \sec \theta \end{bmatrix} \cdot \begin{bmatrix} l/I_x \\ l/I_y \\ l/I_z \end{bmatrix} \tag{8}$$

$f_1(\cdot), f_2(\cdot), f_3(\cdot)$ is the "dynamic coupling part" of the model. Set the controlled output $k_p = \omega_c^2, k_d = 2\omega_c, \omega_c$, as could be seen from 2.1, LESO could totally disturb the three attitude channels $f_1(\cdot), f_2(\cdot), f_3(\cdot)$, use real-time estimators to track and compensate. Therefore, three LADRC controllers could be added in parallel between Y and V to achieve decoupling control of the attitude of the quadrotor. At this point, the actual control quantity $U = [U_1 \ U_2 \ U_3]^T$, could be obtained by $U = B^{-1}(\phi, \theta, \psi, t)V$, and the specific control structure is shown in Fig 2.

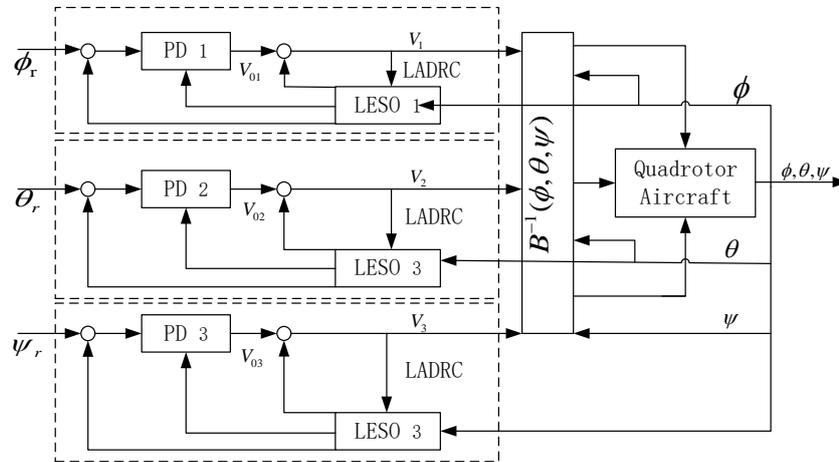


Fig. 2 LADRC attitude decoupling Control structure Diagram

3.3. Parameter tuning

From 2.1, the parameters are adjusted by each LADRC controller, including b_0, ω_0, ω_c . Reference [19] proposes that, in the case where the adjustment time t_s is known, the tuning of the controller parameters could be simplified to the tuning of b_0 , and the specific process could be expressed as:

- (1) Determine the ideal adjustment time t_s ;
- (2) Determine ω_c from $\omega_c \approx 10/t_s$, calculated k_p, k_d by $k_p = \omega_c^2, k_d = 2\omega_c$;
- (3) Let $\omega_0 = 4\omega_c$, after determining the value of k , calculate the gain of LESO, $\beta_1, \beta_2, \beta_3$;
- (4) Select the smaller number as the initial value of b_0 and slowly increase b_0 until satisfactory dynamic performance is obtained.

4. Attitude decoupling control method

The laboratory quadrotor platform was selected and the simulation model was established in Matlab to analyse and verify the performance of the proposed LADRC attitude control method.

The relevant parameters are: $l = 0.23m$, $I_x = I_y = 8 \times 10^{-3} kg \cdot m^2$, $k_b = k_d = 3.13 \times 10^{-5} N \cdot s^2$, $I_z = 2 \times 10^{-2} kg \cdot m^2$

Limited to the length of the article, the design of the controller is verified by taking the pitch channel as an example. According to experience, set the ideal adjustment time $t_{s(\phi)} = 1.5s, k = 6$, and b_0 slowly increases from 0.5 at intervals of 0.1. After many tests, the controlled system can be better when $b_0 = 1$.

The dynamic performance of the ADRC controller is determined by the trial and error method [9], taking $r = 1000$, $h = h_0 = 0.001$, $\alpha_1 = 0.25$, $c = 1$, $\delta = 2 \times 10^{-5}$, $\beta_1 = 100$, $\beta_2 = 300$, $\beta_3 = 1000$. In the experiment, the initial value $\theta = 0^\circ$ is set, When $t = 0s$, $\theta_d = 15^\circ$; $t = 4s$, θ_d changes from 15° to 3° ; at $t = 5s$, the pulse external disturbance signal shown in Fig. 3 is added, and the obtained simulation results are shown

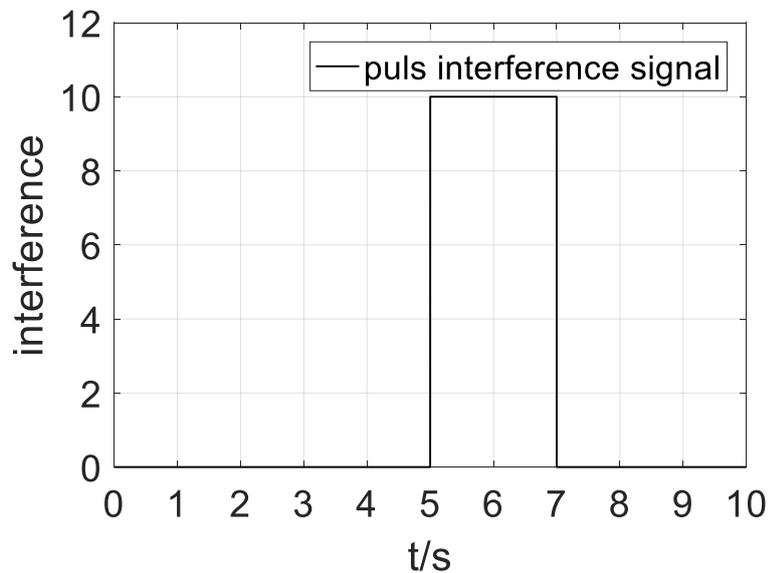


Fig. 3 pulse interference signal

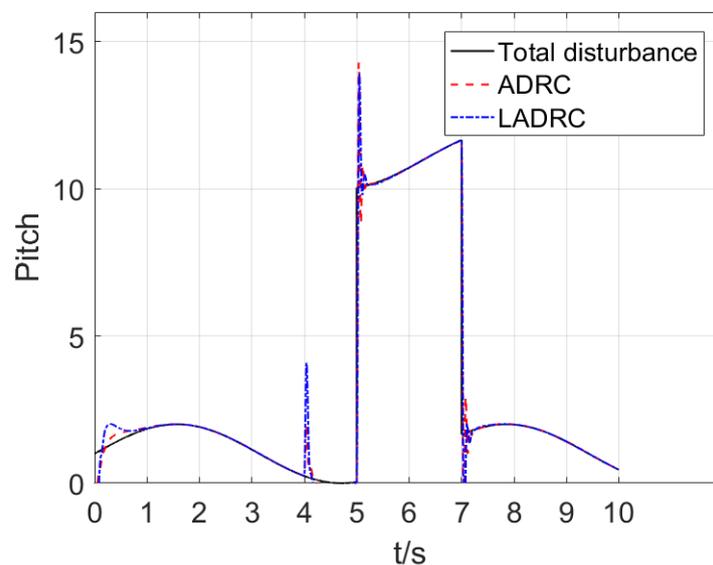


Fig. 4 Pitch channel "total disturbance" and estimation curve

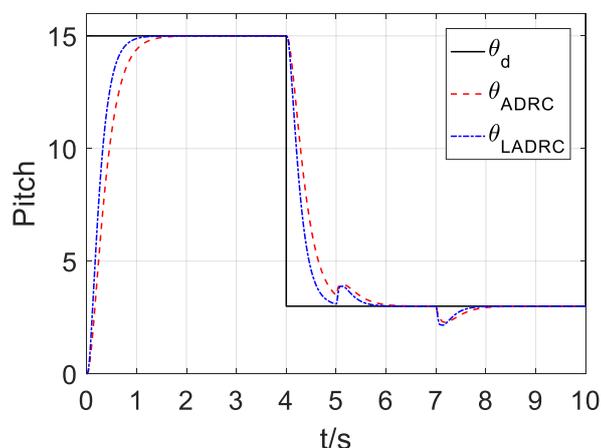


Fig. 5 Tracking response curve of the pitch channel under the interference signal

From Figure 4 and Figure 5, the following conclusions could be drawn:

(1) Both attitude controllers could better track and compensate the “total disturbance” of the pitch channel, but under the existing experimental setting conditions, LADRC has better tracking and compensation effect on the total disturbance;

(2) But under the current experimental settings, the adjustment time of ADRC controller is about 0.77s, and the adjustment time of the LADRC controller is about 0.8s. This is because the parameters that need to be adjusted in the LADRC controller are related to the transition time [20], but the difference between the two is small. Robustness and anti-interference could be quickly converted from the current attitude angle to the target attitude angle without overshoot;

(3) Although the control performance of the two is not much different, the LADRC needs less tuning parameters, and the tuning method is relatively perfect, which is more suitable for application in the engineering field.

5. Conclusion

In this paper, based on the linear active disturbance rejection control technology, an attitude decoupling control method was designed based on the attitude nonlinear coupling model of a small quadrotor. The simulation proved that the controller had strong robustness and the anti-interference ability could effectively control the nonlinear coupling system, and the parameter setting method was simple, which was convenient for engineering realization, and lied a good foundation for the large-angle maneuvering of the four-rotor aircraft. In the next step, the method would be applied to the four-rotor platform built by the laboratory, and further testing would be carried out from the engineering implementation.

Acknowledgments

This work was financially supported by a key laboratory funded project (2017C33013).

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