Quadrotor Flight Control Based on Improved Active Disturbance Rejection Control Technology

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Abstract. This paper proposes a four-rotor attitude control method based on improved active disturbance rejection control. Based on the analysis of the active disturbance rejection controller from the deviation theory, it is found that the extended state observer has problems such as high steady-state error and difficulty in parameter selection. Then, an improved extended state observer was designed structurally, its stability was proved and the error was compared with the traditional extended observer, and the improved auto-disturbance rejection control was applied to the attitude control of the quad-rotor UAV. Finally, the simulation verification of the controller is carried out from various aspects of attitude tracking, height-fixing experiment, external force interference test and wind interference test, and compared with traditional ADRC, the comparison results show that its performance is better than traditional ADRC.

1. Introduction
In recent years, quadcopter wings have been used extensively in reconnaissance, rescue, surveillance, aerial photography and industrial applications. The reason why quadcopter wings have attracted so much attention is their vertical take-off and landing capability, which guarantees excellent manoeuvrability. But the design of controllers to meet the flight requirements still faces many difficulties. A quadrotor UAV is highly susceptible to other adverse factors during flight and is a non-linear, under-driven, strongly coupled system. The design of accurate, efficient and easy-to-implement quadrotor control systems is therefore of great research value and significance.

Literature [1] uses an active disturbance rejection non-singular fast terminal sliding mode control algorithm based on genetic optimization. Literature [2] uses a cascade fuzzy PID control algorithm to achieve flight attitude stability and has achieved good results. Literature [3] introduced the integral backstepping control method of the integral link, designed the system control loop, and verified the feasibility through simulation. Literature [4] uses the Active Disturbance Rejection Controller (ADRC) control method to verify the anti-interference ability of the quadrotor.

In this paper, an improved self-anti-disturbance control is proposed for quadrotor attitude control to address the above issues. The self-anti-disturbance controller is analysed by means of deviation theory, and it is found that the dilated state observer has problems such as high steady-state error and difficult parameter selection. Then, the improved dilated state observer is designed structurally, its stability is demonstrated and its error is compared with that of the conventional dilated observer. Finally, the improved ADRC controller is used to design the flight control rate of the quadrotor UAV and is demonstrated in simulation.
2. Modeling of quadrotor UAV dynamics

The attitude angle of the quadrotor is obtained from the relative positions of the two coordinate systems. Let the coordinates of the quadrotor UAV relative to the origin in the ground coordinate system be \( B = (x, y, z) \). Euler angles are \( \theta = (\phi, \theta, \varphi) \).

The establishment of a quadrotor UAV dynamics model is in fact an abstract mathematical modelling process, so reasonable assumptions need to be made about the actual system before the model is established, in order to achieve a simple and clear model, and to remove the rough and tumble role. Combined with the situation of the quadrotor UAV in actual flight, the following reasonable assumptions are given.

Assumption 1: That the quadrotor UAV has a centrally paired fuselage and that the housing is of absolute steel construction.

Assumption 2: The quadrotor UAV has its centre of mass, its centre and its co-ordinate origin at the centre of the fuselage.

Assumption 3: that the quadrotor UAV has a high rotor speed and light mass, neglecting its own moment of inertia.

Assumption 4: the quadrotor UAV flies at low and slow altitudes without regard to aerodynamic effects.

A model of the dynamical system of the quadrotor can be obtained based on the Newton-Euler modelling approach [5]

\[
\begin{align*}
\ddot{x} &= \left( \sin \psi \sin \phi + \cos \psi \sin \theta \cos \phi \right) \frac{u_1}{m} + d_1 + \dot{\phi} \psi \left( \frac{J_y - J_z}{J_x} \right) + \frac{l}{J_x} u_2 + d_4 \\
\ddot{y} &= \left( -\cos \psi \sin \phi + \sin \psi \sin \theta \cos \phi \right) \frac{u_2}{m} + d_2 + \dot{\psi} \phi \left( \frac{J_z - J_x}{J_y} \right) + \frac{l}{J_y} u_3 + d_5 \\
\ddot{z} &= \left( \cos \theta \cos \phi \right) \frac{u_3}{m} - g + d_3 + \dot{\theta} \phi \left( \frac{J_x - J_y}{J_z} \right) + \frac{l}{J_z} u_4 + d_6
\end{align*}
\]  

(1)

where \( \phi, \theta, \varphi \) are the pitch, roll and yaw angles, respectively, \( m \) is the mass of the quad-rotor UAV, \( g \) is the acceleration of gravity, and \( J \) is the inertia matrix, \( d_i, i = 1, \ldots, 6 \) is the sum of model uncertainty and interference. \( U \) is the input control quantity for each channel and satisfies

\[
\begin{align*}
U_1 &= K_i (\Omega_i^2 + \Omega_i^3 + \Omega_i^4 + \Omega_i^5) \\
U_2 &= K_i (\Omega_i^2 - \Omega_i^3) \\
U_3 &= K_i (\Omega_i^3 - \Omega_i^4) \\
U_4 &= K_i (\Omega_i^4 + \Omega_i^5 - \Omega_i^1 - \Omega_i^2)
\end{align*}
\]  

(2)

The above quadrotor UAV dynamics model is strongly coupled, but the ADRC algorithm proposed in this paper is able to decouple the individual channels of attitude control well. Since the ESO in ADRC can estimate the sum perturbation, ADRC does not explore the specific form of each perturbation between channels, but only estimates the sum perturbation of that channel. In order to achieve better decoupled control of each channel, each channel uses a separate improved ESO to estimate the sum perturbation of that channel and compensate for it at the same time as the system control output, thus better addressing the strong coupling between the channels in attitude control. The attitude loop control system of the quadrotor UAV is shown in Figure1, with its control system divided into four channels, each of which is controlled separately using an improved ADRC.
To facilitate the elaboration of the control strategy, the quadrotor attitude system model is written in the form corresponding to the ADRC theory as follows.

\[
\begin{align*}
\dot{z} &= f_1(z, \dot{z}, \omega_1) + b_1u_1, \\
\dot{\phi} &= f_2(\phi, \dot{\phi}, \dot{\theta}, \psi, \dot{\psi}, \omega_1) + b_2u_2, \\
\dot{\theta} &= f_3(\phi, \dot{\phi}, \dot{\theta}, \psi, \dot{\psi}, \omega_2) + b_3u_3, \\
\dot{\psi} &= f_4(\phi, \dot{\phi}, \dot{\theta}, \psi, \dot{\psi}, \omega_3) + b_4u_4,
\end{align*}
\]

In equation (3), \( f_i(\cdot) \) represents the internal disturbance of the quadrotor system.

3. Design of quadrotor attitude controller

3.1. Improvement of traditional ADRC

The following takes the design of the roll channel controller as an example. According to the internal structure of the improved ADRC, the structure diagram of the roll channel controller can be obtained as shown in Figure 2.

\[
\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= bu + x_3 \\
\dot{x}_3 &= f_2(\phi, \dot{\phi}, \dot{\theta}, \psi, \dot{\psi}, \omega_2) \\
y &= x_1
\end{align*}
\]

3.1.1. Tracking Differentiator

The input signal of the tracking differentiator is \( v_d \) and the output signal is \( v_1, v_2 \). The output signal \( v_1 \) is the tracking signal of the input signal \( v_d \) and \( v_2 \) is the derivative of \( v_1 \). The mathematical expression is.

\[
\begin{align*}
\dot{v}_1 &= v_2 \\
\dot{v}_2 &= f_{han}(v_1 - v, v_2, r_0, h)
\end{align*}
\]
where the function $f_{han}(v_1 - v, v_2, r_0, h)$ is the most rapid tracking function given in the literature [6].

### 3.1.2. Improved ESO based on the deviation principle

(1) The conventional ESO is [7].

\[
\begin{align*}
\dot{e}(t) &= z_1(t) - x_1(t) \\
\dot{z}_1(t) &= z_2(t) - \beta_0 e(t) \\
\dot{z}_2(t) &= z_3(t) - \beta_0 \cdot f(l(e(t), \alpha, \delta)) + bu(t) \\
\dot{z}_3 &= -\beta_0 \cdot f(l(e(t), \alpha, \delta))
\end{align*}
\]

Where $e$ is the deviation between $x_1$'s observed value $z_1$ and $x_1$, $z_2$ is the observed value of $x_2$ and $z_3$ is the observed value of $x_3$. $\beta_1, \beta_2, \beta_3$ are the observed gains and go to positive values. $\alpha, \alpha_2$ are non-linear factors, $\delta$ is a filter factor. $f(l(\cdot))$ is a nonlinear function defined as:

\[
f(l(e, \alpha, \delta)) = \begin{cases} 
\frac{e}{\delta^{1-\alpha}} & |e| \leq \delta \\
|e| \alpha \text{sign}(e) & |e| > \delta
\end{cases}
\]

where $\delta$ is the non-linear factor.

A large number of experiments have shown that the parameter values are chosen to be very large if the tracking adjustment of the pair is to be completed successfully. In general, the parameter values have to be about 10 to 100 times larger, but too large a parameter value can lead to oscillations in the ESO and even to the system eventually becoming unstable. Furthermore, the conventional ESO parameters interact with each other and the choice of parameters becomes difficult, which tends to have an impact on the accuracy of the system. Therefore, it will become important to find a suitable replacement method.

Analysis of the ESO according to the deviation control principle reveals that the conventional ESO regulation of the deviation $e$ of $z_1$ to $x_1$ is achieved by regulating the derivative of the regulation in accordance with the deviation principle, but the regulation of the derivative of $z_2, z_3$ is not the best choice. Therefore, a suitable alternative to the regulation of the derivative of the deviation $e(t)$ to $z_2, z_3$ has to be found.

Transforming equation (6) into the form:

\[
\begin{align*}
\dot{z}_1(t) &= x_1(t) + e(t) \\
\dot{z}_2(t) &= \dot{z}_1(t) + \beta_0 e(t) \\
\dot{z}_3(t) &= \dot{z}_2(t) + \beta_0 \cdot f(l(e(t), \alpha_1, \delta)) - bu(t)
\end{align*}
\]

From equation (4) and equation (6), we get:

\[
\begin{align*}
\dot{z}_1(t) &= \dot{x}_1(t) + \dot{e}(t) \\
&= x_1(t) + \dot{e}(t) \\
\dot{z}_2(t) &= \dot{z}_1(t) + \beta_0 \cdot \dot{e}(t) \\
&= \dot{x}_1(t) + \dot{e}(t) + \beta_0 \cdot \dot{e}(t) \\
&= x_1(t) + \dot{e}(t) + \beta_0 \cdot \dot{e}(t) + bu(t)
\end{align*}
\]

Bringing Eq. (8) into Eq. (9) can in turn be organised to give:

\[
\begin{align*}
\dot{z}_1(t) &= x_1(t) + e(t) \\
\dot{z}_2(t) &= x_2(t) + \dot{e}(t) + \beta_0 \cdot e(t) \\
\dot{z}_3(t) &= x_3(t) + \dot{e}(t) + \beta_0 \cdot \dot{e}(t) + \beta_0 \cdot f(l(e(t), \alpha, \delta)) + bu(t)
\end{align*}
\]
From equation (10), it can be seen that the deviation of $z_1(t)$ from $x_1(t)$ is $e(t)$, the deviation of $z_2(t)$ from $x_2(t)$ is $\dot{e}(t) + \beta_{01} e(t)$, and the deviation of $z_3(t)$ from $x_3(t)$ is $\dot{e}(t) + \beta_{03} \dot{e}(t) + \beta_{02} \cdot fal(e(t), \alpha_1, \delta)$. Therefore, the improved ESO can be designed according to the deviation control principle as:

$$
\begin{align*}
\dot{e}(t) &= z_1(t) - x_1(t) \\
\dot{z}_1(t) &= z_1(t) - \beta_{01} \cdot e(t) \\
\dot{z}_2(t) &= z_1(t) - \beta_{02} \cdot \text{fal}\left[\dot{e}(t) + \beta_{01} \cdot e(t), \alpha_1, \delta\right] + bu \\
\dot{z}_3(t) &= -\beta_{01} \cdot \text{fal}\left[\dot{e}(t) + \beta_{01} \cdot e(t) + \beta_{02} \cdot \text{fal}\left(e(t), \alpha_1, \delta\right), \alpha_3, \delta\right]
\end{align*}
$$

(11)

According to the definition of ESO, the values of $\beta_{01}, \beta_{02}, \beta_{03}$ in equation (12) are all greater than 1. Since the state variables and the derivatives in ESO are continuous and derivable, the order derivatives of $e(t)$ can all be found.

3.1.3 Nonlinear error feedback rate

$$
\begin{align*}
e_{\phi_1}(k) &= \phi_{\phi_1}(k) - z_{\phi_1}(k) \\
e_{\phi_2}(k) &= \phi_{\phi_2}(k) - z_{\phi_2}(k) \\
u_{\phi_0}(k) &= \beta_{04} \cdot \text{fal}\left(e_{\phi_1}(k), \alpha_1, \delta_0\right) + \beta_{05} \cdot \text{fal}\left(e_{\phi_2}(k), \alpha_2, \delta_0\right) \\
u_z(k) &= u_{\phi_0}(k) - z_1(k) / b_\phi
\end{align*}
$$

(12)

Of these:

$$
\text{fal}(e, \alpha, \delta) = \begin{cases} 
e^{\alpha} \text{sgn}\,|\,e\,| > \delta \\
\delta \cdot e^{\alpha} \leq |\,e\,| \leq \delta \\
\end{cases}
$$

(13)

Where $\beta_{04}, \beta_{05}$ are the nonlinear combination coefficients, nonlinear factor $\alpha_1, \alpha_2$ ranges from 0 < $\alpha_1 < 1 < \alpha_2$, $u_{\phi_0}(k)$ is the non-linear combination of $e_{\phi_1}$ and $e_{\phi_2}$, $u_z(k)$ is the formation of the final control quantity, and $b_\phi$ is the compensation factor.

4. Numerical simulation

Considering that the mathematical model, ADRC components, and improved ESO operations are more complicated, this section uses the S function to write each important module, and establishes a simulation model based on the Matlab/Simulink module. Through the principle given in reference [8], the parameters of the improved auto disturbance rejection controller are adjusted. The parameters of ADRC and improved ADRC in each channel without adjustment are chosen as follow, where $r = 2, h_0 = 0.05, \alpha_1 = 0.5, \alpha_2 = 0.25, \delta = 0.01, \alpha_3 = 0.75, \alpha_4 = 1.25, \delta_0 = 0.02$ The parameters of improved ADRC in each channel without adjustment are chosen as follow. In order to compare the performance of the traditional ADRC and the improved ADRC, the controller parameters of the two have the same values. The parameters of the quad-rotor UAV and the controller parameters are shown in Table 1 and Table 2. The simulation sampling period is $h=0.01s$.

| Parameter symbol | m  | g   | l   | $I_x$ | $I_y$ | $I_z$ | $K_t$  | $K_d$  |
|------------------|----|-----|-----|-------|-------|-------|--------|--------|
| Numerical value  | 1.44kg | 9.8m/s² | 0.25m | 0.028kg·m² | 0.028kg·m² | 0.074kg·m² | 4.95×10⁻⁵N·s² | 7.5×10⁻⁷N·s² |

Table 1 Quadrotor UAV parameters
Table 2 Parameters of the self-tampering controller

| Parameters | $\beta_{01}$ | $\beta_{02}$ | $\beta_{03}$ | $b_0$ | $\beta_{04}$ | $\beta_{05}$ |
|------------|--------------|--------------|--------------|-------|--------------|--------------|
| Altitude   | 65           | 475          | 850          | 2.4   | 130          | 90           |
| Roll       | 65           | 475          | 850          | 1.2   | 95           | 55           |
| Pitch      | 65           | 475          | 850          | 1.2   | 95           | 55           |
| Yaw        | 65           | 475          | 850          | 1.2   | 95           | 55           |

4.1. Attitude tracking and height-fixing experiments

Assuming that the initial values of all three attitude angles are 0°, the input signal is a periodically varying sine wave with a 20° increase in roll, pitch and yaw sine waves, the altitude channel starts at 0m and the ideal altitude is 1m, and the system is unaffected by interference, the quadcopter attitude response curve under conventional and modified ADRC control is shown in Figure 3 below.
It can be seen from the attitude response curve in Figure 3 that both the improved ADRC and the traditional ADRC controller can track the given desired signal well. But the improved ADRC controller can track the given signal at a slightly faster speed, and the error is relatively low. From the fixed height response curve in Figure 3, it can be seen that the ADRC controller before and after the improvement has a good fixed height effect. Not only the overshoot is extremely small, but the balance time of the system is also very short. Compared with the traditional ADRC controller, it is improved. The ADRC controller can complete the height setting at a faster speed.

4.2. Anti-interference experiments

The attitude tracking and altitude control experiments only demonstrated a slightly better change in the improved ADRC compared to the conventional ADRC, and did not show a significant improvement. To test the sudden external disturbance capability of the system, a square wave disturbance moment of amplitude \(0.2N \cdot M\) and duration 0.1s was added to the input of each of the three attitude angle channels at \(t = 2s, 4s, 8s\) to simulate the external disturbance with a simulation time of 20s. The output curves of the three attitude angles were

![Experimental response curve for resistance to external disturbances](image)

It can be seen from Figure 4 that in the presence of external force interference, both the improved ADRC controller and the traditional ADRC controller can suppress disturbances to a certain extent, but the improved ADRC exhibits a stronger ability to suppress disturbances.

5. Conclusion

In summary, as well as in simulation experiments, it is shown that the designed improved ADRC has less observation error than the conventional ADRC, and the system converges faster and operates more stably. The improved ADRC is able to estimate disturbances faster and more accurately, and the observation accuracy of the improved ADRC is higher than that of the conventional ADRC, which is conducive to improving the operational performance of the ADRC.

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