DESIGN OF AUTO DISTURBANCE REJECTION CONTROLLER FOR FOUR-ROTOR AEROCRAFT

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ABSTRACT: Aiming at the uncertainties of aerocraft parameters and the sensitivity to external disturbances, an auto disturbance rejection controller (ADRC) for four-rotor aerocraft is designed. Firstly, the principle of ADRC, the design scheme of control system, the algorithm of ADRC and the parameter tuning of ADRC are introduced. Then, the simulation experiment and the result analysis are carried out. On the simulation platform, the stability control, attitude tracking, height control and disturbance resistance experiments are conducted on the ADRC system, and the quantitative analysis is carried out with the cascade PID control system. The simulation results show that the ADRC can not only well estimate and compensate the internal and external interference of the system, but also have very strong disturbance resistance. Moreover, it meets the control requirements of the fast manoeuvre and high stability of the aerocraft and the performance index is obviously superior to that of the cascade PID controller.

KEYWORDS: Four-rotor aerocraft; ADRC; cascade PID control

1 INTRODUCTION

In recent years, with the development of microprocessor technology, the application of new materials and the progress of energy storage technology, unmanned aerial vehicle (UAV) has gradually developed towards the direction of miniaturization and intelligence (Zohra et al., 2014; Wang et al., 2015). As one of the spinning UAV, four-rotor aerocraft has attracted wide attention from universities, research institutions and companies at home and abroad because of its advantages of small size, good manoeuvrability, simple design and low manufacturing cost. The four-rotor aerocraft is very suitable for surveillance and reconnaissance in civilian and military fields (Du et al., 2016). In civil field, four-rotor aerocrafts are mainly used in disaster relief, ground monitoring and aerial photography. Because of their high concealment and reliability, they are also used in military fields such as battlefield surveillance, military reconnaissance and other fields.

Therefore, the four-rotor aerocraft has broad market demand and commercial value. The four-rotor aerocraft is made up of two axes which are perpendicular to each other, which is a non-coaxial butterfly aerocraft. Because of the special design structure of the four-rotor aerocraft, it can realize various flight postures, such as hovering, lateral flight, reverse flight and so on. Compared with fixed-spinning aerocraft, it has the remarkable advantages of fast vertical take-off and landing, and has good flexibility. The rotor of the same coaxial has the same direction of rotation when the four-rotor is in flight, and the adjacent rotor has the opposite direction of rotation. Through its own characteristic, it does not need special reverse torque paddles like the conventional rotorcraft, which can effectively eliminate the reverse torque produced during its flight. As a result, the power consumption of the aerocraft is greatly reduced and the utilization rate of energy is increased (Cabecinhas et al., 2015; Serra et al., 2015).

Because of the particularity of the application field of four-rotor aerocraft, it needs high flight stability and accuracy, and these performances mainly depend on the design of flight control system, and there are many practical difficulties to design the control system that meet the requirements (Errouissi et al., 2017). In the course of flight, the four-rotor aerocraft is easily disturbed by the external environment, and affected by the size of its own rotor and the material, the rotor is easily deformed, so it is difficult to obtain accurate aerodynamic parameters, which makes it difficult to establish the accurate model of the four-rotor aerocraft (Shen et al., 2014). In addition, the four-rotor aerocraft has six degrees of freedom, which are the three linear velocities of the centroid motion and three angular velocities around the centroid. The control of the four-rotor is achieved by the control of its four brushless direct current motors. Therefore, the control system of the four-rotor aerocraft is a four-input and six-output under-driven nonlinear system, which makes the design of control system more complicated and
difficult. Because of its under-driven system characteristics, the system has strong coupling characteristics, and the design of its control system should be guaranteed to have good decoupling and robustness (Tang et al., 2014; Miletić et al., 2015). At the same time, due to the smaller size and lighter mass of the four-rotor aerocraft, the airflow and gust have a great influence on the flight stability in the outdoor environment. In consequence, these external disturbances are specially considered and designed in the design of the control system (Nguyen et al., 2018). Because of the above difficulties, the design of the controller for the four-rotor aerocraft has become a hot spot and difficulty.

2 METHODOLOGY

2.1 Principle of auto disturbance rejection controller

The ADRC consists of three parts, which are the tracking differentiator (TD), the extended state observer and the nonlinear state error feedback (NLSEF) (Guo et al., 2016).

Tracking differentiator. Because the input signal of the controller is slowly changing, the error between the controller and the output signal of the system is small, and the control time of the system can be shortened by increasing the ratio coefficient of the controller. In the meanwhile, the system is not overregulated to achieve "the control target of no overshoot and fast tracking" (Sira-Ramírez et al., 2014). The arrangement transition process enlarges the selection range of ratio coefficient and differential coefficient, reduces the adjustment difficulty and improves the robustness of the controller. At the same time, the arrangement transition process can also make the controller's range of object larger when the controller parameters are constant, that is to say, the controller is more adaptable. In ADRC, nonlinear tracking differentiator is used to arrange the transition process, because tracking differentiator can track the signal. In addition, a high-quality differential signal can be obtained by tracking differentiator (Castañeda et al., 2015).

Extended state observer. The extended state observer is the core part of ADRC. The extended state observer is a state observer for uncertain objects. Its core idea is to extend the disturbance generated by the system uncertainty into a system state and estimate it in real time. The disturbance here includes not only the "external disturbance" produced by the original environment and other external factors, but also the "internal disturbance" caused by the uncertainty of the model. By real-time compensation for the estimated total disturbance, the nonlinear and uncertain objects with unknown disturbances can be converted into "integrator" linear object (Qiu et al., 2014).

Nonlinear state error feedback. After converting the nonlinear object into the "integrator" linear object by dynamic compensation linearization, the next problem to be solved is to design the control law to control the "integrator" system (Ding et al., 2015). The main function of the controller is to restrain the functions of uncertainties and to enable the output of the controlled object track the control target. From the non-smooth effects introduced in the previous section, it can be seen that non-smooth feedback is much better than linear feedback in suppressing uncertainties. On the other hand, if the controller wants to enable the output the controlled object track the target, it needs to be realized by the error attenuation between the given input and the output of the object. The linear feedback can only reach the exponential attenuation in the optimal case, and the non-smooth feedback can reach a given finite time attenuation. As a result, the non-smooth feedback is used to design the control law in ADRC (Zhao et al., 2015).

2.2 Design scheme of control system

The three channels of rolling, pitching and yawing are combined with each other. This is the most difficult problem in the design of the controller, and the ADRC can solve this problem well (Ren et al., 2017). The interaction between different channels is considered as the internal disturbance of the system. Together with the external disturbance caused by the environment, they are used as the total disturbance of the channel. And then, each channel independently estimates the total disturbance in real time by ESO independently, and compensates it to realize the decoupling control. Each channel is transformed from the original nonlinear and inaccurate object into an "integrator" linear system (Hunnekens et al., 2014). The structure of the whole system, as shown in Figure 1, is divided into 4 independent circuits: the height control loop, the pitching control loop, the rolling control loop and the yawing control loop, and the ADRC is applied to each loop, respectively. Through the above analysis, the corresponding form of ADRC theory can be expressed as Formula (1).

\[
\begin{align*}
\dot{z} &= f_1(z, \dot{z}) + \alpha_z + bU_1 \\
\dot{\phi} &= f_2(\phi, \dot{\phi}, \Theta, \dot{\Theta}, \psi, \dot{\psi}) + \omega_2 + bU_2 \\
\dot{\phi} &= f_3(\phi, \dot{\phi}, \Theta, \dot{\Theta}, \psi, \dot{\psi}) + \alpha_3 + bU_3, \\
\dot{\phi} &= f_4(\phi, \dot{\phi}, \Theta, \dot{\Theta}, \psi, \dot{\psi}) + \omega_4 + bU_4
\end{align*}
\] (1)
In Formula (1), \( f_i(\bullet) \) refers to the internal disturbance of the system, \( \psi \) is the external disturbance of each channel, and \( b_i \) indicates the coefficient.

2.3 ADRC algorithm

From the Formula (1), it can be seen that the control objects of the ADRC are all second-order nonlinear uncertain objects, so second-order ADRCs need to be designed to control them. According to the principle of separation, ADRC is divided into three parts: TD, ESO and NLSEF to design. Taking the rolling channel as an example, the discrete ADRC algorithm is presented, and the controlled object is shown in Formula (2).

\[
f(\phi, \dot{\phi}, \theta, \dot{\theta}, \omega, \omega + bu, y = \phi (t)
\]

The arrangement transition process (TD) is shown in Formula (3).

\[
\begin{align*}
    v_1(k+1) &= v_1(k) + Tv_1(k) \\
    v_2(k+1) &= v_2(k) + T\text{fst}(v_1(k) - \phi_0(k), v_2(k), r, h)
\end{align*}
\]

The estimated state and total disturbance (ESO) are shown in Formula (4).

\[
\begin{align*}
    z_0(k+1) &= z_0(k) + T(z_0(k) - \beta_1 e_1) \\
    z_1(k+1) &= z_1(k) + T(z_1(k) - \beta_2 \text{fal}(e_1, \alpha_1, \delta) + bu(k)) \\
    z_2(k+1) &= z_2(k) + T \beta \text{fal}(e_1, \alpha_1, \delta)
\end{align*}
\]

The formation of control quantity (NLSEF) is shown in Formula (5):

\[
\begin{align*}
    e_1 &= v_1(k) - z_1(k) \\
    e_2 &= v_2(k) - z_2(k) \\
    u_0(k) &= k_1 \text{fal}(e_1, \alpha_1, \delta_0) + k_2 \text{fal}(e_1, \alpha_2, \delta_0) \\
    u(k) &= u_0(k) - \frac{z_2(k)}{b}
\end{align*}
\]

The control algorithm only needs input data \( u(k) \) and output data \( y(k) \) of the objects. ADRC is a control method which is not based on object model, so it is not necessary to analyze the stability of the controller for specific objects. Therefore, as long as the appropriate parameters are selected, the ADRC can make the four-rotor aerocraft achieve attitude stability and height stability.

![Figure 1. Control system structure based on ADRC](image-url)
and observer parameters $\beta_1$, $\beta_2$ and $\beta_3$, respectively. The value of $\alpha$ determines the nonlinear shape of fal function. In ESO, it generally takes $\alpha_1=0.5$ and $\alpha_2=0.25$. $\delta$ indicates the linear area width of fal function near the origin, and the selection of $\delta$ has great impact on the performance of ESO. The proper $\delta$ can make output signal stable and smooth, and improve the efficiency of non-smooth feedback. If $\delta$ is too large, the majority of ESO works in the linear area. As a result, it cannot show the superiority of non-smooth feedback, and its approximation ability to nonlinear signals will be greatly weakened, and it cannot even track some disturbance signals with relatively large amplitude. If $\delta$ is too small, the fal function is close to the switching function, and high frequency flutter appears easily near the origin.

The observer parameters $\beta_1$, $\beta_2$ and $\beta_3$ are the feedback gains of state error feedback, which affects the convergence speed of ESO. The larger $\beta_1$ is, the faster the speed of z1 tracking input signal is. $\beta_2$ has no great impact on the control quality within the certain order of magnitude, and its size is irrelevant with sampling frequency. In general, it is in the same order of magnitude with sampling frequency. When $\beta_1$ is higher than the order of magnitude, it is easy to cause the divergence of the observer; if it is lower than the order of magnitude, the tracking effect of the observer will be worse. The larger $\beta_2$ is, the faster the speed of z2 tracking input signal differential is. If $\beta_2$ is too large, it will results in the high frequency noise generating in the system; if it is too small, it is easy to cause the oscillation of the observer. An observer's delay in estimation of the disturbance is related to $\beta_3$, and the larger $\beta_3$ is, the smaller the delay in estimation of the disturbance is. However, if $\beta_3$ is too large, it will lead to the oscillation of the observer, and the suppression of noise is also relatively weak. There is a mutual restriction between the three parameters. Properly increasing $\beta_1$ and $\beta_2$ can effectively restrain the oscillation of the observer caused by too large $\beta_3$. Therefore, the adjustment of these three parameters should be coordinated. When adjusting $\beta_3$, it is necessary to properly adjust $\beta_1$ and $\beta_2$ and continuously improve the estimation effect.

Parameter adjustment of nonlinear state error feedback control rate. In ADRC, the NLSEF number has six adjustable parameters, which are nonlinear parameters $\alpha_1$, $\alpha_2$ and $\delta_0$ of fal function, controller gains $k_1$ and $k_2$, and compensation coefficient $b$, respectively. For controller gains $k_1$ and $k_2$, $k_1$ can be regarded as the ratio coefficient of PD controller. The larger $k_1$ is, the faster the speed of the system response is, and the shorter the transition process is. Whereas, if $k_1$ is too large, it will lead to the increase of system oscillation times, even causing the output divergence. $k_2$ can be seen as differential coefficient and increasing $k_2$ can suppress overshoot in the transition process and improve the dynamic performance of the system. However, if $k_2$ is too large, it will lead to early braking, and the adjustment time becomes longer.

The compensation coefficient $b$ is the only variable related to the controlled object in the ADRC. When the model of the controlled object is unknown, it can also be set as a parameter. The different $b$ values determine that the real-time estimates of the total disturbance vary in different ranges and the compensation components will change, that is to say, $b$ is equivalent to the ratio coefficient of the total system disturbance compensation.

3 RESULTS AND DISCUSSION

Based on the theoretical study of ADRC, an ADRC controller is built in MATLAB/Simulink environment as shown in Figure 2. The TD module, the ESO module and the NLSEF module are written in the MATLAB language, and then encapsulated into the S-function module, which can set different parameters by double clicking the dialog box that the module pops out.

Figure 2. Internal structure of roll controller
Then, the parameters of the controller are designed and the control period is T=0.01. According to the parameter selection principle given in the previous part, the parameters of the ADRC are determined by several simulation experiments.

### 3.1 Stability control experiment

First, the effect of ADRC on the stability control of aircraft is verified. The initial values of the three attitude angles of the four-rotor aero craft are the rolling angle $\phi_0 = 30^\circ$, the pitching angle $\theta_0 = 15^\circ$, and the yawing angle $\psi_0 = 10^\circ$. The initial height is 0m and the sampling period is T=0.01. The control target is to make the aero craft achieve stable attitude at a height of 2m. The simulation results are shown in Figure 3 and the performance index is shown in Table 1.

![Image](image1.png)

![Image](image2.png)

![Image](image3.png)

**Table 1. Stability control test performance index**

<table>
<thead>
<tr>
<th>Channel</th>
<th>$t_s$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rolling channel</td>
<td>0.12</td>
</tr>
<tr>
<td>Pitching channel</td>
<td>0.16</td>
</tr>
<tr>
<td>Yawing channel</td>
<td>2.0104</td>
</tr>
<tr>
<td>Height channel</td>
<td>2.0525</td>
</tr>
</tbody>
</table>

From Figure 3, it is seen that the attitude angle and height very stably achieve the expected values, and there is no oscillation in the adjustment process. From the analysis of the performance indexes in Table 1, it can be seen that the ADRC is rather ideal for the stability control of the four-rotor aerocraft. It can achieve stable attitude within 1.5s and reach the target height of about 2s. Compared with the performance index of the stability control experiment using cascade PID controller, the attitude angle and height overshoot are greatly reduced, and the stability of the system is stronger.
Figure 3. Stability control of experimental attitude angle and height response curve

3.2 Comparison experiment between ADRC and cascade PID controller

Next, the control performance of ADRC and cascade PID controller is further compared by the following three experiments.

Attitude angle tracking experiment. The initial value of three attitude angles is set to 0 degree, and the given signal is a periodically changed square wave, in which the square wave gain of the rolling and the pitching channel is 30 degrees, the square wave gain of the yawing channel is 15 degrees, and the frequency is 0.1 HZ. Under the control of ADRC and cascade PID controller, the output curve of the system is shown in Figure 4.

As can be seen from Figure 4, the attitude angular response curve of the ADRC can well track the expected value basically without overshoot. Although the attitude angle response curve of the cascade PID controller can track the expected value, it will cause oscillation. This is because there is a strong coupling among the rolling, pitching and yawing three channels when the three attitude angles change simultaneously, and the change of the other channels will affect the current attitude angle. The ADRC can take the interaction between different channels as internal disturbance of the system, and make real time estimation and compensation through ESO, so there is no mutual interference among the three channels.
Height control experiment. The initial height is set to 0m, and the expected height is 2m and 5m, respectively. The output curves of the system are shown in Figure 5 and Figure 6 under the control of the ADRC and the cascade PID controller. The performance indicators of the two control schemes are shown in Table 2.
Table 2. Height control experimental performance index

<table>
<thead>
<tr>
<th>Simulation conditions</th>
<th>Control scheme</th>
<th>$\sigma$ %</th>
<th>$t_i$(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected height of 2m</td>
<td>Cascade PID controller</td>
<td>22.119</td>
<td>3.27</td>
</tr>
<tr>
<td></td>
<td>ADRC</td>
<td>2.052</td>
<td>2.12</td>
</tr>
<tr>
<td>Expected height of 5m</td>
<td>Cascade PID controller</td>
<td>40.131</td>
<td>3.86</td>
</tr>
<tr>
<td></td>
<td>ADRC</td>
<td>1.279</td>
<td>2.8</td>
</tr>
</tbody>
</table>

From Figure 5, Figure 6 and Table 2, it can be seen that, compared with the ADRC, the overshoot of the height response curve of the cascade PID controller is very large and the adjustment time is long. This is more obvious after the expected height increases. Under the condition of expected value of 5m, the overshoot of cascade PID control is over 40%, the adjustment time is 3.86s, and the control effect is not ideal. The ADRC has a good performance in the case of expected value of 2m and 5m. The overshoot is only about 2%, and when the expected value is 10m and even larger, it can also achieve "fast tracking control target without overshoot". The ADRC controller solves the contradiction between the speediness and overshoot of PID control by arranging the transition process. The TD response curve of the height channel is used to analyze how the ADRC controller arranges the transition process. The results are shown in Figure 7 and Figure 8.

![Figure 7. Height channel TD response curve (tracking output)](image)

![Figure 8. Height channel TD response curve (differential output)](image)

It can be seen from Figure 7 and Figure 8 that, when the stage hopping changes in the current expectation, TD arranges a transition process for it. Its output $v_1$ tracks the input signal $z_d$, and $v_2$ is the differential of $v_1$. The ADRC controller can reasonably arrange the transition process through TD, soften the change of $z_d$, and reduce the overshoot of the system output.

Disturbance resistance test. In the actual system, affected by the sensor noise, the sensor noise is stimulated by adding Gaussian white noise to the feedback variables of three attitude angles. In addition, it is necessary to consider the situation that the attitude angle will be changed by the external disturbance. At the time of 5s, 10s and 15s, the angular acceleration of the rolling, pitching and yawing loop is added to the rectangular wave with the amplitude of 20 and the pulse width of 1s as a mutation signal to test the disturbance resistance of the controller. Under the control of ADRC and cascade PID controller, the output curve of the system is shown in Figure 9.
As can be seen from Figure 9, for external disturbances, the aerocraft can return to the stable state within 2s under the regulation of the cascade PID controller and the ADRC, indicating that the two controllers have a certain anti-interference performance. In contrast, the ADRC performs better. In the range of the same external disturbance, the ADRC can achieve good anti-interference effect, mainly due to the effect of ESO.

4 Conclusion

The four-rotor aerocraft has wide application prospects in both civil and military fields. Because of the particularity of the application field of the four-rotor aerocraft, it needs high flight stability and accuracy, which mainly depends on the design of the control system. Based on the profound analysis of the motion control characteristics of the four-rotor aerocraft, the control method of the four-rotor aerocraft is preliminarily studied by taking full consideration of the nonlinear, under-driven, strong coupling and model uncertainty of the control system. The main results are as follows:

First, the effectiveness of the four-rotor aerocraft flight control system based on ADRC is verified by simulation experiments. The simulation results show that the ADRC can realize attitude stabilization control and altitude control well, and has the advantages of small overshoot and short adjustment time. Second, the application of ADRC technology provides a new way to solve the control problem of the four-rotor aerocraft. The design of the ADRC does not need the controlled object model, which solves the problem that the four-rotor aircraft is difficult to accurately model, and simplifies the design of the controller. Therefore, the controller is simple in structure, small in calculation and easy to be realized in engineering. It can be well used to estimate and compensate the
internal disturbance and external disturbance by the extended state observer. Moreover, it can well overcome the strong coupling among the three attitude angles of the aerocraft. It has good dynamic performance and it can meet the control requirements of fast maneuverability and high stability for four-rotor aerocraft attitude. In summary, ADRC has broad application prospects in the field of four-rotor aerocraft control.

5 References


