The Design of Height Control System of Fully Autonomous UAV Based on ADRC-PID Algorithm

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Abstract. In order to solve the problem of low data accuracy due to UAV height sensing equipment such as GPS, barometer, ultrasound, etc., a control system used on multi-rotor aircraft was designed to achieve UAV autonomous altitude cruise. In response to this problem, we introduce an inertial measurement unit (IMU), and use the IMU to calculate the system acceleration (ACC), and use the Kalman algorithm to predict altitude, thereby eliminating altitude drift caused by insufficient sensor accuracy and errors. In addition, the ADRC-PID joint control algorithm is also introduced to control the attitude of the aircraft, achieve control compensation, and finally control the height of the drone through the three-loop cascade PID.

1. Introduction
Nowadays, the multi-rotor UAV automatic control technology is relatively mature, but the near-Earth altitude control is often restricted by factors such as low sensor accuracy and ground efficiency, and its control is also very difficult. Therefore, the study of altitude control systems for fully autonomous UAV operations has an important meaning.

For the UAV height control algorithm, the traditional cascade PID control algorithm is used for UAV take-off and landing control [1], but there are often cases where the aircraft swings up and down to affect the control performance; the current domestic and foreign research focuses on the UAV High-accuracy height measurement is achieved through multi-sensor fusion [2, 3], but they ignore the dynamic performance of the drone during flight; at the same time, there are also proposals for new near-ground sensors to improve flight control performance according to the application, because Ignoring the complexity of the ground makes the practicality greatly reduced [4].

The design circuit uses discrete components to improve the circuit structure, and in the form of a two-stage amplification circuit, the entire system can simultaneously meet high gain and the best noise coefficient. Compared with the high-level requirements of out-of-band suppression, the performance of the existing solution is much improved.

In view of the above problems, this paper proposes to use a three-loop cascade PID controller and ADRC-PID controller to control the altitude and attitude control system, so as to ensure the stability of the flying attitude of the drone during the operation.
2. Design of Aircraft Self-stability Control Algorithm
The traditional cascade PID controller [5, 6, 7] is a typical linear controller. When it is applied to the typical nonlinear control system of quadrotor UAV, there are inherent unavoidable defects, so ADRC (Active Disturbance Rejection Control) is a control method that combines the PID controller [8, 9, 10] and the PID controller. This control method not only ensures the response speed of the drone, but also uses the characteristics of the ADRC controller. Get good control effect when the external disturbance is unknown.

2.1. ADRC-PID Control Algorithm
The equations for the control system of the aircraft can be obtained:

\[
\begin{align*}
\frac{dx_1}{dt} &= f_1(x_1) + x_2 \\
\frac{dx_2}{dt} &= f_2(x_1, x_2, t) + bu(t) \\
y &= x_1
\end{align*}
\]  

Where:
- \(x_1\) -- Angular velocity data input
- \(x_2\) -- time
- \(t\) -- System parameters
- \(u(t)\) -- System nonlinear combination output
- \(y\) -- The final output of the system

Suppose \(f_1(x_1), f_2(x_1, x_2, t)\) are known, and \(x_1, x_2\) are measurable. Using the state variable \(x_2\) as the "virtual control variable" \(U_1\) to control state variable \(x_1\), you can set:

\[U_0 = U_1 - f_1(x_1)\]  

Substituting the above formula into the equation, formula is written as follows:

\[
\frac{dx_1}{dt} = U_0
\]  

By designing reasonable parameters and determining appropriate error feedback to design \(U_0\), the variable \(x_1\) can track the time-varying trajectory \(u(t)\). In order to achieve stable control of the system, it is only necessary to design an auto disturbance rejection controller with appropriate parameters between \(x_2\) and \(u(t)\). The ADRC controller can be combined with the traditional cascade PID controller. First, the traditional single-loop PID controller is used to control the angle error of the pitch angle \(\theta\), roll angle \(\phi\), and yaw angle \(x\) of the aircraft. Then, the angular velocity error is controlled by the ADRC controller, and the control quantity is finally output to the aircraft's power system. The flow chart is as follows, where \(c_1, c_2, z_1, z_2, z_3, b\) are system parameters.

2.2. Design of auto disturbance rejection controller

2.2.1. Tracking differentiator. Extracting the available differential signal from the signal contaminated by noise is the premise of accurately controlling the attitude of the drone. This requires the design of a suitable differentiator to extract the differential signal. The expression is as follows:
\[
\begin{align*}
\begin{cases}
\dot{x}_1 = x_2 \\
\dot{x}_2 = -r^2[x_1 - v \cdot \text{trns}(T_0, t)] - 2rx_2 \\
y = x_2
\end{cases}
\end{align*}
\] (4)

Where:
\[
\text{trns}(T_0, t) = \begin{cases}
\frac{1}{2}(1 + \sin(\pi(\frac{t}{T_0} - \frac{1}{2}))), t \leq T_0 \\
1, t > T_0
\end{cases}
\] (5)

Where:
- \(v\) -- Reference signal
- \(x_1\) -- Tracking reference input signal
- \(x_2\) -- Tracking error of reference input signal
- \(\tau\) -- Time constant
- \(\text{trns}(T_0, t)\) -- Transition process function

The transition process is arranged mainly to reduce the initial deviation between the feedback and the reference value, so that the contradiction between the stabilization time and overshoot can be avoided.

2.2.2. Extended State Observer (ESO). Set \(x_1 = \Delta v, x_2 = \Delta \omega, x_2 = f\), then equation (1) can be written as:
\[
\begin{align*}
\begin{cases}
\dot{x}_1 = \Delta v \\
\dot{x}_1 = x_2 = \Delta \omega \\
\dot{x}_2 = x_3 + bu(t) = f + bu(t) \\
\dot{x}_3 = \omega
\end{cases}
\end{align*}
\] (6)

Where \(x_3\) -- State observation variables, which represent internal and external interference.

The above equation is a third-order differential equation, and a third-order state observer can be used to observe the state quantity of the system of equations. The state observer is as follows:
\[
\begin{align*}
\begin{cases}
e_1 = z_1 - y \\
\dot{z}_1 = z_2 - \beta_1 e_1 \\
\dot{z}_2 = z_3 - \beta_2 e_1 + bu(t) \\
\dot{z}_3 = -\beta_3 e_1
\end{cases}
\end{align*}
\] (7)

Where
- \(z_1\) -- Estimate of \(v\)
- \(z_2\) -- Estimate of \(\omega\)
- \(z_3\) -- Estimated amount of unknown external disturbance
- \(\beta = [\beta_1 \ \beta_2 \ \beta_3]^T\) -- Observation parameter vector

The state observer adds the estimated interference to the input of the drone system to compensate for the actual interference, and does not need to know the specific form of external interference, which is why the ADRC controller performs well in anti-interference.
2.2.3. Nonlinear combination. By adjusting the appropriate parameters, the expanded state observer can output the estimated quantities of $x_1$, $x_2$, and $x_3$, set to $\hat{x}_1$, $\hat{x}_2$, $\hat{f}$, respectively. Suppose the reference signal output by the tracking differentiator is $v_e$, and the output differential signal is $v_e$.

Set $e_1 = v_e - x_1$, $e_2 = v_e - x_2$, then the control algorithm expression can be written of $u(t)$ can be written as:

$$u(t) = \left(\frac{1}{b}\right)(-\hat{f} + k_1e_1 + k_2e_2)$$  \(8\)

Where $k_1, k_2$ -- control gain.

Through the above formula design parameters, the UAV can achieve attitude control performance with no overshoot, small delay, and resistance to external interference.

3. The Design of Aircraft Altitude Control Algorithm

UAV operations are mostly carried out in the low-altitude field, which requires maintaining a stable flying attitude. Therefore, the flight-like flight of the aircraft needs to be made more reliable and safer through the altitude control algorithm.

3.1. Highly Cascade PID Controller

The single-loop PID performs PID calculation on a group of feedback and input separately and outputs the actuator, but generally the single-loop PID controls a physical quantity of the controlled object, such as the attitude angle of the drone. The control quality of single-loop PID is low. If you need to further increase the anti-interference ability and damping of the system, you need to introduce cascade PID control [11].

The traditional PID controller is composed of proportional, integral, and derivative terms. Assuming that the controller output is:

$$u(k) = K_pe(k) + K_i\sum_{n=0}^{k}e(n) + K_de(k) - e(k - 1))$$  \(9\)

Where $e(k)$ is system input. The schematic diagram of the cascade PID controller of proportional $K_p$, differential $K_d$ and integral parameters $K_i$ is as follows:

Figure 1. Controller schematic of three-ring cascade PID.

The height controller is a PID controller that controls the amount of height error and uses the output as the input to the height speed controller. The altitude speed controller performs error control on it, and the output result is input to the altitude acceleration controller, and finally to the motor.
4. Experimental results

4.1. ADRC+PID joint control algorithm test

In order to better control the attitude of the aircraft during the cruise process, the ADRC+PID joint control method is used to control the aircraft attitude. Taking the pitch motion angle as an example, compare the ADRC+PID joint control, cascade PID control and pure ADRC The test results of the algorithm control are shown in Figure 2 (assuming that the expected deflection angle is 5 degrees and the initial is 0 degrees):

![Figure 2. Reference ideal height curve.](image)

It can be seen from Figure 2 that the ADRC algorithm can be used to obtain better control results, with a short rise time and small overshoot, but the ADRC algorithm needs to adjust more parameters. When the aircraft angle and angular velocity are controlled by the ADRC algorithm it is inevitable that the parameters will not reach the best effect of the theory, so simply using the ADRC algorithm, its rise time is more than the method of combining the ADRC algorithm and the PID algorithm. Of course, the ADRC algorithm can significantly suppress overshoot compared to the PID algorithm. The specific data is shown in Table 1:

|               | ADRC+PID | ADRC | PID |
|---------------|----------|------|-----|
| Overshoot/%  | 3.9      | 4.2  | 10.1|
| Adjustment time/s | 0.73  | 1.19 | 3.42|
| Rise Time/s  | 0.56     | 0.91 | 0.92|

It can be seen from the Table 1 that the control algorithm using ADRC+PID not only retains the small feature of ADRC overshoot, but also utilizes the rapidity of PID algorithm to control the attitude of the UAV.

5. Conclusion

After we use Kalman filtering to process the height data of the drone, the drone can perform a fixed-height cruise well. At the same time, we adopt the control method that combines the ADRC auto-disturbance controller and the PID controller to make it unmanned. The machine can obtain better control effect under the condition of unknown disturbance from the outside world.

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