Design of Control System for Small Quadrotor Based on NLADRC

Bo Li, Min Tao
China Satellite Maritime Tracking and Control Department, Jiangyin 214431, China

Abstract. Aiming at the problem of poor stability and low control precision of small quadrotor, a set of flight control system based on (Non Linear Active Disturbance Rejection Control, NLADRC) was designed. Firstly, on the basis of analysing the principle of quadrotor flight, a mathematical model of small quadrotor was established. Secondly, the hardware system was designed modularly, the hardware of each module was selected. Then, the quaternion attitude calculation algorithm was used to fuse the attitude data of the accelerometer and the gyroscope, and the four channel (pitch, roll, yaw, height) were controlled by the NLADRC. Finally, the experiment showed that the quadrotor can fly smoothly in the mode of hover.

1. Introduction
The small quadrotor is a small, light-weight, low-cost, and simple-to-maneuver aircraft. The prospects for future development are also very broad. Quadrotor UAV is a typical nonlinear coupled under actuated system, and flight control is difficult. To solve this problem, this paper designs a small quadrotor flight control system based on NLADRC and designs a hardware system based on STM32. The software system is designed based on quaternion attitude fusion algorithm and NLADRC algorithm. The experimental results show that the control system can effectively control the quadrotor.

2. Quadrotor flight principle and modelling
The quadrotor is a criss-crossing structure with four symmetrical rotors. The rotors are controlled by motors. Attitude control is achieved by changing the speed of each motor. Among them, rotors 1 and 3 rotate counterclockwise, and rotors 2 and 4 rotate clockwise to balance the anti-torque torque generated by rotor rotation. During hovering, the four rotors rotate at the same speed; at the same time, the rotation speed of the four rotors is changed by the same amount, and the quadrotor has no chance to rise or fall; the rotation speed of one rotor is increased, and the rotation speed of the other rotor in the same group is reduced by the same amount.

Set up the inertial coordinate system as the system and the body coordinate system as the system. To simplify the calculation and analysis, set the following:

1. In the system, gravity acceleration is constant regardless of changes in the curvature of the earth.
2. In the course of sports, the quadrotor UAV is considered as a rigid body, without considering the effects of high-frequency vibration and deformation.
3. The center of gravity and point of the quadrotor UAV coincide.
4. The mass and the moment of inertia of the quadrotor UAV are unchanged.
5. The quadrotor UAV is only lifted by gravity and propellers during the movement.

According to [1], the mathematical model of the quadrotor UAV is:
\[
\begin{align*}
\ddot{\theta} &= \frac{1}{I_y} \left[ lu_\theta + \dot{\phi} \psi (I_z - I_y) + J_{\text{rotor}} \Omega \dot{\phi} \right] \\
\ddot{\psi} &= \frac{1}{I_x} \left[ lu_\psi + \dot{\theta} \psi (I_y - I_x) - J_{\text{rotor}} \Omega \dot{\theta} \right] \\
\ddot{\phi} &= \frac{1}{I_z} \left[ lu_\phi + \dot{\phi} \dot{\phi} (I_z - I_y) \right] \\
\ddot{z} &= g - \cos \theta \cos \phi \frac{1}{m} u_h
\end{align*}
\] (1)

Among them, \(I_x, I_y, I_z\) is the inertia moment of the body around the \(X, Y, Z\) axis, \(l\) is the distance from \(O\) to the center of mass of the motor, \(J_{\text{rotor}}\) is the moment of moment of the rotor, \(\Omega = -\Omega_1 + \Omega_2 - \Omega_3 + \Omega_4\) is the equivalent rotation speed of the motor; \(u_\theta, u_\phi, u_\psi, u_h\) is pitch, roll, yaw and height control respectively. The corresponding relationship between the four motor speeds and the four channel control amounts is shown in equation (2):

\[
\begin{bmatrix}
\Omega_1^2 \\
\Omega_2^2 \\
\Omega_3^2 \\
\Omega_4^2 
\end{bmatrix} =
\begin{bmatrix}
-k_1 & -k_2 & k_1 & k_2 \\
-k_1 & k_1 & k_2 & k_3 \\
k_1 & k_1 & -k_2 & k_3 \\
k_1 & -k_1 & k_2 & k_3 
\end{bmatrix}
\begin{bmatrix}
u_\theta \\
u_\phi \\
u_\psi \\
u_h
\end{bmatrix}
\] (2)

Among them, \(k_1\) is the control coefficients for the pitch and roll channels, \(k_2\) is the yaw control coefficients, \(k_3\) is the height control coefficients.

3. System hardware design

The control system adopts a modular design. The hardware system consists of a main control module, a power supply module, a remote control receiver module, a posture measurement module, a position measurement module, and a motor module. The attitude data is collected by the attitude measurement module, and the position data is measured by the position measurement module. The main control module performs fusion calculation on the collected data to calculate the current attitude and position of the aircraft. According to the control instructions received by the remote control receiving module, certain values are used. The control law generates a motor drive signal and inputs the motor module to achieve control of the attitude and position of the aircraft.

3.1. Main control module

The control system adopts STM32F103C8T6 as the main control chip. The microcontroller has 9 communication interfaces, which are convenient for receiving attitude position data. The microcontroller has 7 timers and can receive commands issued by a remote controller and can be used
3.2. Power Module
The power module includes a lithium battery and a voltage regulator circuit. The battery used in the system is a 3.7V lithium battery. The battery is full of 4.2V. When the battery voltage is lower than 3.6V, the voltage will drop sharply, and the full load voltage drop of the buck chip MIC5219 is 500mV. Therefore, the voltage regulator circuit includes a boost circuit and a step-down circuit. The boost circuit increases the battery voltage to 5V, and the step-down circuit further reduces the voltage of 5V to 3.3V.

3.3. Attitude and Position Measurement Module
The attitude measurement module adopts 6-axis MPU6500 from MRS, and a 3-axis gyroscope and a 3-axis accelerometer are integrated into the MPU6500. The full-scale measurement range of the gyroscope and accelerometer can be adjusted according to actual needs. The MPU6500 uses the SPI method to communicate with the STM32 main control module, and the communication rate can reach up to 20M/Hz.

Position measurement module adopts HC-SR04 ultrasonic distance measuring module. The module adopts dual probe form, one shot and one receive. The detection precision is 0.3cm, and the detectable distance is 2cm-400cm.

3.4. Motor Module
The main control module outputs 4 PWM signals to the motor module. Because the motor uses 720 hollow cup motors, the current is not very large. Therefore, the motor drive circuit adopts an NMOS circuit to realize the control of the rotation speeds of the four motors.

3.5. Remote Control Receiver Module
The remote controller sends an eight-channel 2.4 GHz remote control signal to the PPM receiver. The receiver module uses the input capture function to capture the PPM signal. The CD4051 analog electronic switch will decompose the PPM signal into four PWM signals and then decompose the signal. PWM signal input to the main control module.

4. System Software Design
The control system software is designed in the KeilμVision5 development system. The system initialization is performed first. The main control module initializes the serial port, interrupts, PWM output, MPU6500 initial value, barometer, and ultrasonic distance meter. Enter the interrupt, determine whether to unlock, if it is unlocked, then perform a gesture update, the frequency is 1 KHz, to obtain the current posture information of the drone. Convert the remote control signal, obtain the desired attitude of the drone, carry out the control law calculation, and obtain the PWM input value of each motor, and control the four motors with a frequency of 500 Hz. Control system software program flow shown in Figure 1:
4.1. Attitude Update

Posture updating is the core part of flight control system. The accuracy and speed of attitude calculation directly affect the effect of flight control. This system adopts quaternion-based attitude calculation algorithm.

First, read the data of MPU6500, and perform the sliding filter processing on the accelerometer measurement data to obtain the latest arithmetic mean value, and use the average value as the accelerometer measurement value.

Then the quaternion is initialized. According to Euler's finite rotation theorem, quaternion is to regard the rigid body's attitude movement as a certain angle rotation around a certain rotation axis, ie, the shortest path between two attitude rotations, in which Instantaneous rotation axis, rotation angle, construction quaternion:

\[
Q = \cos \frac{\theta}{2} + u^p \sin \frac{\theta}{2} = \cos \frac{\theta}{2} + \cos \alpha \sin \frac{\theta}{2} i_\theta + \cos \beta \sin \frac{\theta}{2} j_\theta + \cos \gamma \sin \frac{\theta}{2} k_\theta = q_0 + q_1 \vec{i}_\theta + q_2 \vec{j}_\theta + q_3 \vec{k}_\theta
\] (3)

During the flight, the severe buffeting of the airframe will affect the accelerometer. The measurement noise is large and the reliability is not high in a short time. The data measured by the gyroscope in the short term is more accurate, but it has the characteristic of temperature drift. Accumulative errors will occur after working for a long time. Therefore, the posture of the gyroscope needs to be corrected by the attitude obtained by the accelerometer.
\( g_b \) is the attitude obtained by integrating the gyroscope to the body, \( a_b \) represents the attitude measured by the accelerometer. The error between the two can be expressed as a cross product, as shown in Equation (4):

\[
e = a_b \times g_b = \begin{bmatrix} a_y v_z - a_z v_y \\
                            a_z v_x - a_x v_z \\
                            a_x v_y - a_y v_x 
\end{bmatrix} = \begin{bmatrix} e_x \\
                            e_y \\
                            e_z 
\end{bmatrix}
\] (4)

This error is input to the PI controller to correct the gyro integration posture, as shown in equations (5) and (6):

\[
\begin{bmatrix} e_{x\text{lt}} \\
                e_{y\text{lt}} \\
                e_{z\text{lt}} 
\end{bmatrix} = \begin{bmatrix} e_{x\text{lt}} + K_i e_x \\
                            e_{y\text{lt}} + K_i e_y \\
                            e_{z\text{lt}} + K_i e_z 
\end{bmatrix}
\] (5)

\[
\begin{bmatrix} \omega_x \\
                \omega_y \\
                \omega_z 
\end{bmatrix} = \begin{bmatrix} \omega_x + K_p e_x + e_{x\text{lt}} \\
                            \omega_y + K_p e_y + e_{y\text{lt}} \\
                            \omega_z + K_p e_z + e_{z\text{lt}} 
\end{bmatrix}
\] (6)

Among them, \( e_{x\text{lt}} \), \( e_{y\text{lt}} \), \( e_{z\text{lt}} \) is the error integral, used for eliminating the static drift of the gyroscope; \( K_i \) is the integral coefficient, \( K_p \) is the proportional coefficient, through adjusting \( K_p \) and \( K_i \), the accelerometer to revise the gyroscope measurement value can be controlled; \( \omega_x \), \( \omega_y \), \( \omega_z \) are the gyroscope's measured values that represent three axis actual angular velocity.

The quaternion is updated by solving a quaternion differential equation. The quaternion differential equation is shown in equation (7):

\[
\begin{bmatrix} \dot{q}_0(t) \\
                \dot{q}_1(t) \\
                \dot{q}_2(t) \\
                \dot{q}_3(t) 
\end{bmatrix} = \begin{bmatrix} 0 & -\omega_3 & -\omega_2 & -\omega_1 \\
                            \omega_3 & 0 & -\omega_1 & -\omega_2 \\
                            \omega_2 & \omega_1 & 0 & -\omega_3 \\
                            -\omega_1 & \omega_2 & \omega_3 & 0 
\end{bmatrix} \begin{bmatrix} q_0(t) \\
                            q_1(t) \\
                            q_2(t) \\
                            q_3(t) 
\end{bmatrix}
\] (7)

The quaternion update equation, as shown in equation (8):

\[
\begin{bmatrix} q_0(t+1) \\
                q_1(t+1) \\
                q_2(t+1) \\
                q_3(t+1)
\end{bmatrix} = \begin{bmatrix} q_0(t) \\
                            q_1(t) \\
                            q_2(t) \\
                            q_3(t) 
\end{bmatrix} + \frac{\Delta T}{2} \begin{bmatrix} -\omega q_4 - \omega q_2 - \omega q_3 \\
                            \omega q_0 - \omega q_3 + \omega q_2 \\
                            \omega q_1 + \omega q_0 - \omega q_4 \\
                            -\omega q_2 + \omega q_3 + \omega q_0 
\end{bmatrix}
\] (8)
In the process of quaternion update, quaternions lose their normalization due to errors and other interference factors, and need to be renormalized so that the quaternion is finally converted to Euler angles and the attitude measurement values are obtained. As shown in equation (9):

\[
\begin{bmatrix}
\theta \\
\varphi \\
\psi \\
\end{bmatrix} = \begin{bmatrix}
\arctan\left(\frac{2(q_0q_2 + q_1q_3)}{q_0^2 + q_1^2 - q_2^2 - q_3^2}\right) \\
-\arcsin\left(2(q_1q_3 - q_0q_2)\right) \\
\arctan\left(\frac{2(q_2q_3 + q_0q_1)}{q_0^2 - q_1^2 - q_2^2 + q_3^2}\right)
\end{bmatrix}
\]

(9)

4.2. NLADRC-based control law design

The NLADRC algorithm is a control algorithm that has been developed rapidly in recent years and is widely used. NLADRC absorbs the advantages of the classic PID control algorithm and improves it. It does not depend on the system exact model. It eliminates errors with process errors. It has the advantages of simple algorithm, small overshoot, strong anti-interference, etc. The control system has good Dynamic and steady state performance. This system obtains three attitude angles and height expectation values according to the remote control signal conversion, and applies the NLADRC controller to the four control channels of pitch, roll, yaw and altitude to adjust the voltages of the four motors according to the motor control law. The quadrotor control, control law block diagram shown in Figure 2:

Figure 2. Block diagram of control law

Among them, \(\theta_d\) is the expected pitch angle, \(\varphi_d\) is the expected roll angle, \(\psi_d\) is the expected yaw angle, \(\theta\) is the actual pitch angle, \(\varphi\) is the actual roll angle, \(\psi\) is the actual yaw angle, \(u_\theta\) is the pitch control amount, \(u_\varphi\) is the roll The transfer control amount, \(u_\psi\) is the yaw control amount, \(u_h\) is the height control amount, \(V_i^i (i=1,2,3,4)\) is the value of the first motor voltage.

The NLADRC controller consists of a tracking differentiator (TD), an extended state observer (ESO), and a nonlinear state error feedback law (NLSEF). The pitch channel is used as an example. The block diagram of the ADRC controller is shown in Figure 3:
The tracking differentiator is used for arranging the transition process. It is obtained by tracing at a certain speed, and is obtained by extracting the differential signal. For the second-order system, a discrete form of nonlinear tracking differentiator is used, as shown in formula (10):

\[
\begin{align*}
\theta_{d1}(k+1) &= \theta_{d1}(k) + h\theta_{d2}(k) \\
\theta_{d2}(k+1) &= \theta_{d2}(k) + h\delta t(\theta_{d1}(k) - \theta_{d}(k), \eta, h)
\end{align*}
\] (10)

Among them, for the sampling period, the expected pitch angle is the parameter for determining the speed of tracking.

The extended state observer not only can observe the system state, but also can realize the estimation of the model uncertainty and the added disturbance, and dynamically compensate the estimated total interference to the control quantity to realize the suppression of the interference and enhance the system's robustness. The stickiness is the core part of the NLADRC. The pitch control amount and the actual pitch angle value are input to the extended state observer, so that the observation of the pitch angle, the observation of the pitch rate, and the observation of the total pitch of the pitch channel can be obtained, and the pre-compensation control can be used.

Among them, \( b \) is the compensation factor for determining the compensation effect, \( e \) is the difference between the observed value and the actual value, \( \beta_1, \beta_2, \beta_3 \) is the observer gain coefficient, \( f_{al}(e, \alpha, \delta) \) is a saturation function and \( \alpha_1, \alpha_2 \) is adjustable parameter, and \( \delta \) is the length of the linear segment interval.

The nonlinear state error feedback law combines the error between the transition process and the state estimation and its differential signal to generate a pitch control quantity. This system uses a nonlinear combination of saturation functions.

After a large number of debugging experiments, the parameter reference values of the four-channel NLADRC controller are shown in Table 1:
Table 1. NLADRC controller parameters

| AISLE  | TD  | ESO  | NLSEF |
|--------|-----|------|-------|
| Pitch  | $\eta = 80$, $b = 1.9 \times 10^{-5}$, $\beta_1 = 30$, $\beta_2 = 300$, $\delta = 0.01$, $k_1 = 0.8$, $k_2 = 1.2$, $\delta_1 = 0.02$ |
| Roll   | $\eta = 80$, $b = 1.9 \times 10^{-5}$, $\beta_1 = 30$, $\beta_2 = 300$, $\delta = 0.01$, $k_1 = 0.8$, $k_2 = 1.2$, $\delta_1 = 0.02$ |
| Yaw    | $\eta = 80$, $b = 1.3 \times 10^{-5}$, $\beta_1 = 30$, $\beta_2 = 410$, $\delta = 0.01$, $k_1 = 0.8$, $k_2 = 1.2$, $\delta_1 = 0.02$ |
| Height | $\eta = 80$, $b = 3.0 \times 10^{-5}$, $\beta_1 = 30$, $\beta_2 = 500$, $\delta = 0.01$, $k_1 = 0.8$, $k_2 = 1.2$, $\delta_1 = 0.05$ |

5. Conclusion
This paper designs a quadrotor control system. The control system uses STM32 as the main control module, measures attitude and altitude data through MPU6500 and barometer, uses quaternion attitude calculation algorithm to update the attitude, and uses four-channel NLADRC control. The controller controls the rotation speeds of the four motors to achieve a stable control of the attitude and altitude of the flight. The flight experiment results verify the effectiveness of the hardware system and the software system, which lays the foundation for the next flight experiments in an outdoor wind disturbance environment.

References
[1] Xue Liang, Wang Xinhua, Jason, et al. Design of Attitude Control System for Multi-rotor UAV Based on Fuzzy PID [J]. Electronic Design Engineering, 2016, 24 (16): 61 - 63.
[2] Feng Changhui, Qi Xiaohui, Su Lijun, et al. Design of TD-PD control law for quadrotor UAV [J]. Electro-optics & Control, 2016 (3): 36 - 40.
[3] Jeong S, Jung S. Design, Control, and Implementation of Small Quad-Rotor System Under Practical Limitation of Cost Effectiveness [J]. International Journal of Fuzzy Logic & Intelligent Systems, 2013, 13 (4): 324 - 335.