Design of the Outdoor Cruising Control System of the Quadrotor Drone

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Abstract. During the outdoor cruising flight of the UAV, it will often cause problems such as inaccurate positioning information and course to drift due to interference of sensor signal errors, ground effects, airflow, and communication delay. In this paper, an outdoor cruising control system of the quadrotor drone is designed, where the Kalman filter and the Mahony filter are adopted to fuse the sensor data to obtain the attitude to be controlled, and the PID control method is introduced to reduce the external noise to the control system. As a result, the GPS/INS combined navigation method was used to design the quadrotor drone controller. The system improves the anti-jamming capability of the aircraft, has the advantages of real-time, fast response, and high precision, and can realize the positioning cruise function of the quadrotor aircraft in a complex outdoor environment.

Keywords: Quadrotor drone, flight controller, integrated navigation, PID control, filter fusion.

1. Introduction
With the continuous enrichment of UAV application scenarios [1-4], the requirements for flight controllers are getting higher. The small unmanned aerial vehicle (UAV) researched by Carnegie Mellon University [5] has realized hovering and low-speed cruising functions well. R. Mahony et al. [6] designed by the backstepping method has a fast response time and no overshoot, and it has good robust trajectory tracking performance. Vijay Kumar [7] have designed an infrared-assisted attitude detection system with good stability and robustness. Beijing University of Aeronautics and Astronautics [8] proposed a sliding mode variable structure control law based on a noise filter differentiator without using an angular rate sensor. Northwestern Polytechnical University [9] proposed a new adaptive Kalman filter algorithm and achieved good simulation results. Nankai University [10] designed a nonlinear tracker to analyze the swaying process caused by the load. The research on the autonomous navigation function of the UAV has the following directions: IMU, GPS, integrated navigation, image positioning-based autonomous positioning cruise, and laser ranging-based autonomous positioning cruise. The aircraft will be affected by various aspects when performing outdoor operations in the air, such as ground effect interference, airflow interference, communication delay, sensor signal error, etc., which brings great challenges to the design of anti-jamming controllers. The delay caused by long-distance communication and sensor signals will have a great impact on the
accurate control of the system. It has extremely important practical significance and application value for the research of fusion algorithms of quadrotors.

2. Design of the control system of the quadrotor drone

The flight controller controls the operation of peripheral hardware, the flight status of the aircraft and communication with the host computer, which mainly includes inertial sensor units (MPU6500 and LSM303D), programming simulation units, altitude position information sensor units (MS5611 and U-Blox) and communication unit (Bluetooth 2.4G), etc. The inertial measurement unit is used to calculate the attitude of the drone. The altitude position information sensor unit is used to obtain the actual height of the drone and the precise position of the world coordinates. The communication unit is used to perform data transmission with the control end. The block diagram of the flight controller hardware is shown in Fig. 1.

The design of the software flow pattern is shown in Fig. 2. Firstly, when the system is turned on, the hardware and software modules must be initialized. Secondly, the working status of the peripheral hardware should be detected, and the working state of the power unit can be judged by the ESC alarm sound. Thirdly, obtain and initialize the sensor data, wait for peripheral control commands. Finally, after receiving the control signal, the capture and comparison module peripheral to the microcontroller analyzes the control signal and sends the control command to the main controller system. In the process of attitude control and system control, first of all, the main controller regularly collects sensor data through a timer and processes the attitude sensor data to obtain the pitch angle rate. And then, the data of the gyroscope, accelerometer, and magnetometer are fused to obtain the current state of the aircraft. According to the command, it is to predict the state of the aircraft in the next state. After the attitude adjustment, the controller will prejudge and control the aircraft through the PID algorithm, then the control signal is transmitted to the power unit to complete the entire control process.

![Figure 1. The block diagram of the flight controller hardware.](image-url)
3. Data processing algorithm

During the flight, due to external vibration, wind resistance, and other high-frequency interference signals, the sliding window average filter method is used to preprocess the gyroscope and acceleration sensor data. When the system is initialized, $n$ groups of values $h_i$ of the gyroscope are read and averaged to obtain the zero offset value $h_0$. The actual value $h_i'$ can be obtained as (1) below. It will make the system susceptible to external noise during the flight when $n$ is too small. Conversely, the excessive length will passively increase the system delay. The data filtering method of the acceleration sensor is similar to that of the gyroscope.

$$
\begin{align*}
    h_0 &= \frac{1}{n} \sum_{i=1}^{n} h_i \\
    h_i' &= (h_i - h_0) \\
    a_0 &= \frac{1}{n} \sum_{i=1}^{n} a_i \\
    a_i' &= (a_i - a_0)
\end{align*}
$$

Figure 3. The Mahony filter.

The zero point drift occurs after the gyroscope is used for some time, which will increase the integral error, and the acceleration sensor is easily susceptible to deviation caused by the interference of external noise or body vibration. This design is improved based on the Mahony filter (Fig. 3), revising the rotation angular velocity. The posture estimate value $R_{y'}$ obtained from the fusion of accelerometer and the magnetometer data is combined with the angular velocity $\Omega_y$ measured by the
gyroscope to update posture estimate value $\hat{R}$. The Mahony filter takes the deviation as a correction amount and inputs it to the controller, and uses the output as the correction value for the gyroscope angular velocity measurement value, which takes a short time to obtain a good estimate.

The GPS provides the position and heading information of the aircraft, while INS provides various types of navigation information such as the speed, position and attitude angle of the aircraft [11, 12]. The GPS/INS integrated navigation system solves the problem of GPS data transmission interruption in a short time when the aircraft is in a special location (indoors, tunnels, and narrow roads between buildings, etc) so that the system can be accurately positioned, and the position can be quickly tracked. By the extended Kalman filter, the position error can be bounded and the position output can be more continuous, which can keep the navigation system stable for a long time. The system state of the quadrotor drone is established as:

$$\mathbf{X} = \begin{bmatrix} \mathbf{P} \\ \mathbf{V} \\ \mathbf{q} \end{bmatrix}$$  \hspace{1cm} (2)

Where: position vector $\mathbf{P} = [P_x, P_y, P_z]^T$; velocity vector $\mathbf{V} = [V_x, V_y, V_z]^T$; attitude quaternion $\mathbf{q} = [q_1, q_2, q_3, q_4]^T$. After linear conversion, discrete processing and first-order approximation, the system equations is expressed as:

$$\mathbf{X}_k = \Phi_{k|k-1}\mathbf{X}_{k-1} + \Gamma_{k-1}\mathbf{w}_{k-1}$$ \hspace{1cm} (3)

$$\mathbf{Z}_k = \mathbf{H}_k\mathbf{X}_k + \mathbf{v}_k$$ \hspace{1cm} (4)

After the previous calculation, the system compares the set speed with the actual speed to obtain the difference as the control input of the PID controller, performs proportional integral differential control, and finally converts the output into an electrical signal, drives the ESC to control the aircraft power system to achieve the purpose of adjusting the system stability. The PID control formula is as follows:

$$u(k) = K_p e(k) + K_i \sum_{j=0}^{k} e(j) dt + K_d \frac{d[e(k) - e(k-1)]}{dt} + u(0)$$ \hspace{1cm} (5)

Where: $e(k)$ is the error between the initial value of the controller and the current value; $dt$ is the control period; $K_p$ is the proportional coefficient; $K_i$ is the integral coefficient, $K_d$ is the differential coefficient; $u(0)$ is the basic quantity of the motor speed regulation.

4. Test results and analysis
In order to verify the control effect of the aircraft controller, the aircraft is tested, and the aircraft and test environment are shown in Fig. 4.

Figure 4. The aircraft and test environment.
The proportional adjustment makes the system start to oscillate (Fig. 5). The most intuitive expression of differential adjustment is to suppress proportional adjustment, reduce the oscillation caused by proportional adjustment, and keep the system stable at one point. During the process of actual flight control, differential adjustment suppresses overshoot and stabilizes the aircraft more quickly. The curve (Fig. 6) stabilizes at a static error value of -3°. Through integral adjustment, static errors can be eliminated and balance can be achieved in principle.

**Figure 5.** The system oscillation of the UAV.

**Figure 6.** The static error of the UAV.

**Figure 7.** The anti-interference of the UAV.

**Figure 8.** The stable state of the UAV.
As shown in Fig. 7, the aircraft is disturbed by external forces during smooth flight. The time required for the system to complete the adjustment within two oscillations and return to a stable state, which indicates that the system and parameters have strong anti-jamming capabilities. In Fig. 8, after increasing the integral adjustment, the system reaches a steady state in about 200ms, which meets the delay requirement. In order to verify the effectiveness of the system, the outdoor autonomous cruise flight was carried out. The test results show that the aircraft has a good flight response and achieves the functions of one-button autonomous take-off, fixed-point cruise, and a smooth landing back to the take-off point.

5. Conclusion
In this design, the Mahony filter improved is used to fuse sensor data to solve the problem of course drift during the flight. By using the extended Kalman filter to fuse the combined navigation data, it solves the problem that the aircraft's positioning data transmission is interrupted at a special position in a short time so that the aircraft can use the inertial navigation system to accurately locate. The aircraft attitude is controlled by the PID controller to improve the flight response speed, anti-jamming capability, and robustness, which can improve the aircraft's cruise performance and working efficiency in complex outdoor environments. But there are still deficiencies in some extremely harsh signal environments. In the future, we will introduce a vision module for positioning assistance to further prompt performance and expand application scenarios.

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