Design of four-rotor autonomous target-dropping aircraft based on image processing

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Abstract. The aim of this study is to design and produce a quad-rotor autonomous target shooting aircraft based on STM32F407 microprocessor and OV7725 image acquisition system. Herein, the quaternion is defined by using Euler's theorem, navigation coordinate system and carrier coordinate system. Taking STM32F407 master controller as the core, the control system of the aircraft is composed of, distance measuring and height setting module, six-axis motion sensor measurement module, three-axis magnetometer measurement module and camera unit trajectory tracking module. Then, four circuits of the flight control system were designed, including the main control circuit, attitude measurement circuit, throwing rake control circuit and image processing circuit. In addition, three algorithms related to aircraft were prepared, including attitude control cascade PID algorithm, height control algorithm and attitude solution algorithm, and an image processing software was designed. On this basis, the aircraft was built, and finally its flight attitude, height, fixed point, and hover were tested. The results showed that all the algorithms are correct, and the aircraft can successfully pitch, roll, yaw, recognize image trajectory, and automatically drop materials and cruise.

1. Introduction

Quadrotor aircraft is a new type of small UAV, which has high mobility and agility and can complete hover, vertical start and low-speed cruise and other flight tasks. It is widely used in military detective, disaster monitoring, aviation mapping, agricultural plant protection and other fields. It is not easy to control of the quadrotor aircraft steadily. And it is related to many factors of the aircraft. In recent years, scholars at home or abroad have proposed some new control methods for quad-rotor UAV, such as the linear PID control of self-adaption, synovial re-configurable control, the tracking control of attitude of self-adaption of Robust, the structure control of retro-step synovial variable and so on[1-3]. Among them, the accuracy and speed of the attitude solution of the quadrotor aircraft affect directly the stability of the reliability and implementation of the algorithm of the aircraft control. Therefore, attitude solution is the premise of the control of quadrotor aircraft. With the development of micro-electro-mechanical technology and computer technology, the low-cost gyroscopes and accelerometers of quadrotors have many advantages, such as small size, light weight, low power consumption, high cost performance, etc.. Inertial measurement unit, the attitude measurement system of aircraft has been widely used.

Based on the existing research results, a four-rotor autonomous target-shooting vehicle is designed and fabricated in this paper. The main contents include[4-6]:

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The quaternion is defined in combination with the Euler's theorem, the navigation coordinate system and the carrier coordinate system to calculate the attitude of the quadrotors.

The overall scheme of the system hardware is designed. that is to say, with the STM32F407 master controller as the core, the flight control system is also composed of four parts, ranging and height setting module, six-axis motion sensor measurement module, three-axis magnetometer measurement module and camera unit track tracking module.

The main control circuit, attitude measurement circuit, rake control circuit and image processing circuit of the flight control system are designed.

The design of software of the system includes the cascade PID algorithm, the altitude control algorithm, the attitude algorithm and the image processing software design.

The double closed-loop control strategy is adopted in the control of whole four-rotor vehicle system.

The quadrotor aircraft was built and the performance test was carried out to verify the correctness of the algorithm.

### 2. Quadrotor aircraft attitude algorithm

In order to ensure the normal operation of the aircraft, the attitude measurement system needs to update the attitude information of the carrier in real time to compensate the change of base motion. In the attitude estimation system of aircraft, the navigation coordinate system Oxynzn and the carrier coordinate system Oxbybzb should be defined first.  The navigation coordinate system adopted in this paper is the local geographic coordinate system, in which the directions of coordinate axes Oxn, Oyn and Ozn are taken east, north and celestial (ENU) respectively. In the coordinate system of the carrier (System B), along the horizontal axis of the carrier Oxn is to the right, Oyn is to the forward and Ozn is to the upward. Oxn, Oyn and Ozn correspond to the pitching axis, horizontal roller axis and yaw axis of the carrier respectively.

According to Euler's theorem[7-9]: When the navigation coordinates Oxynzn are rotated to the carrier coordinates Oxbybzb, and the euler angles are pitch Angle $\theta$, roll Angle $\gamma$ and yaw Angle $\psi$ respectively. The attitude transformation matrix can be obtained by rotation:

$$C^b_s = \begin{bmatrix}
\cos \gamma \cos \psi + \sin \gamma \sin \theta \sin \psi & -\cos \gamma \sin \psi + \sin \gamma \sin \theta \cos \psi & -\sin \gamma \cos \theta \\
\cos \theta \sin \psi & \cos \theta \cos \psi & \sin \theta \\
\sin \gamma \cos \psi - \cos \gamma \sin \theta \sin \psi & -\sin \gamma \cos \psi - \cos \gamma \sin \theta \cos \psi & \cos \gamma \cos \theta
\end{bmatrix}$$

Quaternion is an indirect method to solve the attitude transformation matrix. The solution of the differential equation of the direction cosine matrix can be used to replace by the solutions of quaternion differential equations, which is obtained by solving the quaternion differential equation. Assume that F is the vector of the attitude quaternion between the navigation system coordinate system and the carrier coordinate system[10-14].

(1) Definition of quaternion.

Four parameters are used to construct a three-dimensional complex space. Among them, two parameters determine the direction of the axis, one determines the rotation Angle, and the other determines the scaling ratio. Assuming that the current coordinate system of the aircraft is the coordinate system of the body, the quaternion definition is:

$$F = [f_0, f_1, f_2, f_3]^T = [1000]^T$$

(2) Normalization of acceleration value.

After filtering the attitude sensor data, the acceleration data Acx, Acy, Acz and are angular velocity data Acx, Acy, Acz obtained. And the filtered acceleration value is normalized:
Quaternion is used to represent the components of triaxial gravity force \( G_x, G_y \) and \( G_z \) (components of gravity unit vector in the coordinate system of the body).

\[
\begin{align*}
G_x &= 2(f_1 f_3 - f_0 f_2) \\
G_y &= 2(f_1 f_0 - f_2 f_3) \\
G_z &= f_0^2 - f_1^2 - f_2^2 + f_3^2
\end{align*}
\]

(4) Calculate the errors between the accelerometer measurement value and gravity component.

\[
\begin{align*}
e_x &= a_x + G_x - a_z + G_y \\
e_y &= a_z + G_y - a_x + G_z \\
e_z &= a_x + G_y - a_y + G_x
\end{align*}
\]

(5) Compensating the measured value of the gyroscope with error correction. Quaternion update attitude data by using gyroscope as data source. The gyroscope has accumulated errors in the integration process. The difference between the acceleration measuring by accelerometer and the value calculated by gyroscope integral is the deviation of the gyroscope. And the measurement value of the gyroscope is corrected with deviation.

In the formula, \( k_i \) and \( k_P \) parameters are the proportional and integral constants for adjusting the accelerometer to correct the gyroscope error, and the updated value of the error are \( \hat{\epsilon}_{\text{int}} \).\( \hat{\epsilon}_{\text{int}} \), \( \hat{\epsilon}_{\text{int}} \) and \( \hat{\epsilon}_{\text{int}} \).

(6) Quaternions updated. The quaternions are updated with the above corrections:

\[
\begin{align*}
f_0 &= \hat{f}_0 + \frac{dt}{2}(-f_1 \times Av_f - f_2 \times Av_f - f_3 \times Av_f) \\
f_1 &= \hat{f}_1 + \frac{dt}{2}(-f_2 \times Av_f - f_3 \times Av_f - f_1 \times Av_f) \\
f_2 &= \hat{f}_2 + \frac{dt}{2}(-f_3 \times Av_f - f_1 \times Av_f - f_2 \times Av_f) \\
f_3 &= \hat{f}_3 + \frac{dt}{2}(-f_1 \times Av_f - f_2 \times Av_f - f_3 \times Av_f)
\end{align*}
\]

In the above equation, the \( \hat{f}_0 \sim \hat{f}_3 \) represent the updated value of the quaternion.

(7) Normalization processing of quaternion. With the introduction of the error, the module of quaternion is not equal to 1. And the quaternion must be normalized when calculating Euler angles with updated quaternion. Here is the quaternion normalization of quaternion:

\[
\begin{align*}
f_0 &= \hat{f}_0 (f_0^2 + f_1^2 + f_2^2 + f_3^2)^{-\frac{1}{2}} \\
f_1 &= \hat{f}_1 (f_0^2 + f_1^2 + f_2^2 + f_3^2)^{-\frac{1}{2}} \\
f_2 &= \hat{f}_2 (f_0^2 + f_1^2 + f_2^2 + f_3^2)^{-\frac{1}{2}} \\
f_3 &= \hat{f}_3 (f_0^2 + f_1^2 + f_2^2 + f_3^2)^{-\frac{1}{2}}
\end{align*}
\]

(8) The solution of attitude angle. The attitude Angle was calculated by using the normalized quaternion. The attitude Angle is calculated as follows:

\[
\text{Roll.Angle} = \tan^{-1} \left( \frac{2(q_x q_y - q_w q_z)}{1 - 2(q_i^2 + q_j^2)} \right)
\]
\[ \text{Pitch Angle} = \sin^{-1}(2 \times (q_0q_2 - q_1q_3)) \] (9)

3. System hardware design

3.1. General scheme design of the system

The flight control system is based on STM32F407 master controller. The main modules include KS103 ranging and height setting module, MPU6050 six-axis motion sensor measurement module, HMC5883 three-axis magnetometer measurement module and OV7725 camera unit trajectory tracking module[15]. The block diagram of the hardware of four-rotor aircraft flight control system is shown in Figure 1.

3.2. The circuit design of flight control system

3.2.1. The circuit of main control. The microcontroller STM32F407 is the core control unit of the system in the aircraft. The STM32407 series MCU is a processor based on the Cortex-M4 kernel. It has the advantages of low power consumption and fast processing speed, and the maximum operating frequency is up to 168MHz, and 16 channel DMA controller, and supporting timer, ADC, SPI, IIC, USART and other peripherals. The minimum system can realize the control function of four-rotor aircraft which is composed of STM32F407 microcontroller mainly includes clock circuit, reset circuit and J-Link interface. The clock circuit is composed of 8M Hertz crystal oscillator and starting capacitor, which provides a stable clock source signal to the SCM. The reset circuit is composed of a key and a 33PF capacitor, which is used to filter the high frequency jitter when the key is pressed.

3.2.2. The circuit of attitude measurement. Attitude sensor MPU6050 and course detection HMC5883L were used for attitude measurement circuit. MPU6050 chip integrated three-axis accelerometer and three-axis gyroscope, and used for attitude parameter measurement. The chip has one I2C interface. When the pull resistance is connected on the CLK and SDA pin, the chip can inhibit communication interference resistance. A small-capacity bypass capacitor can filter out high frequency interference, which connected parallel to the power supply of the chip. And the chip communicate with main controller through I2C way, as shown in figure 2.

The three-axis magnetometer of Hmc5883L is a kind of heading measurement sensor. The inertial measurement sensor, with I2C communication interface and HMC118X series high-resolution reluctance sensor internal integrated, automatic demagnetization device, amplifier, deviation calibrator, etc., is used to measure the magnetic field strength of the earth and realize the course measurement of aircraft. The circuit is shown in Figure 3.

3.2.3. Target control circuit. Objects are hanged and controlled by electromagnetic coil of the aircraft through adsorption. The circuit is shown in Figure 4: The control circuit of the electromagnetic coil is
composed of 8,050 audion, relay and IN4007 secondary tube. While the high level signal of the control signal line is transmitted through the controller, the relay coil is energized and the switch is closed for adsorption. The normally open contact of the relay is closed. The motor is powered on to work, and the material is hung up. When the controller transmits the low level signal controlled, the relay coil is cut off, and the motor cut off, the material is put out. And the IN 4007 serves is a continuation current diode which eliminates the effect of the reverse electromotive force of the coil on the circuit.

**Figure 3.** Course measurement circuit diagram

**Figure 4.** Circuit diagram of target dropping control

### 3.2.4. Image processing circuit
The image processing circuit collects the ground track image and recognizes the image through the camera. And the camera adopts A CMOS digital image sensor of model OV7725, which supports the output of images with a maximum resolution of 300000 pixels (640x480 resolution). It is small in size, low in working voltage, and supports the output of image data when using VGA. Coordinate data of image track output by the image processing circuit is transmitted to the flight control system and realize ground track recognition.

### 4. System software design

#### 4.1. Cascade PID algorithm for aircraft attitude control
The attitude control of aircraft is the main factor in the stable flight of aircraft. To change the attitude of flight, the four motor speeds of aircraft should be changed, and the attitude control of aircraft flight is affected by the current attitude. In this paper, cascade PID controller is selected. And the flow chart of cascade PID control of aircraft attitude is shown in Figure 5. The Angle and angular speed are adjusted by cascade PID. The Angle is used as the outer ring, the angular speed as the inner ring, and the motor speed is controlled by 4-channel PWM output. After the aircraft motor unlocking and taking off, the data of MPU6050 and HMC5883 are collected and filtered every 2ms, and the attitude calculation is carried out. The difference between the calculated data and the given Angle is compared, and the result is input into the attitude PID controller. Whether the value of PID output is greater than 1200 which is the maximum throttle value set by the program. Otherwise, the program is terminated.

#### 4.2. Aircraft altitude control algorithm
The quality of image acquisition is affected by the flight altitude of the aircraft and the maximum focal length of the camera. To acquire accurate image data, the aircraft must fly steadily at a certain altitude. And the position type PID controller must be used for the height control of aircraft. The flight height of the aircraft is collected every 3ms[16]. After mean filtering of the sampled values, it is used as the measured value of the height PID controller, as shown in Figure 6.
4.3. Algorithm for attitude determination of aircraft
The current attitude angle is obtained by using inertial measurement sensors from aircraft. The data of MPU6050 and HMC5883 MEMS sensors are obtained through I2C bus communication of the flight control system controller. And the measured data are filtered and processed, after which the attitude is calculated. The current attitude angle can be calculated and analyzed by the gyroscope and the accelerometer, which are equipped in the MPU6050 sensor. And after filtering the two data, the data fusion is carried out[17]. The program flow of attitude solution is shown in Figure 7.

![Figure 5. Attitude Control Program Flowchart](image)

![Figure 6. Altitude Control Program Flowchart](image)

4.4. Design of aircraft image acquisition and processing software
Through the DMA peripheral of STM32F407, the camera is initialized and the coordinate data of trajectory image is written to SRAM in the double-buffering mode. Using STM32F407 dual buffer mode of DMA peripherals, the controller kernel runs the image processing algorithm in the foreground and reads the buffer to the SRAM in the background, which will further compress the image processing time. The position coordinates and flight speed of the target point relative to the aircraft are obtained by image preprocessing, extraction of effective points and trajectory recognition algorithm, and the flight mode is switched according to the coordinate characteristics. The filtered position coordinates, velocity, and flight pattern data are transmitted to the attitude controller, and the procedure is shown in Figure 8.
5. Aerocraft system debugging

5.1. Adjustment of the flight altitude
The position PID controller is adopted on the height control. In order to ensure the flight height stability of the aircraft, the value of the PID output should not be too large. At first, proportional $K_p$, integral $K_i$ and differential $K_d$ are set to zero. According to the flight height stability of the aircraft, $K_p$ is adjusted at first and then $K_i$ and $K_d$ parameters successively. When the aircraft can fly stably at the set height and does pitch and roll movements, and the altitude does not change. Then the parameters are set successfully. The setting parameters are shown in Table 1.

|     | P  | I   | D   |
|-----|----|-----|-----|
| Height | 3.2 | 0.01 | 0.03 |

5.2. Aerocraft attitude debugging
The attitude control adopts cascade PID controller composed of angular velocity loop and angular loop. When the PID parameters are adjusted, start from the inner ring is adjusted at the first. And the three parameters of proportional $K_p$, integral $K_i$ and differential $K_d$ are set to zero. Observing the flight condition of the aircraft, $K_p$ parameters is adjusted, then $K_i$ and $K_d$ parameters in turn. The parameters of the inner ring can be stabilized when the aircraft no longer has displacement relative to the ground. In the same way, the parameters of the outer ring are adjusted[18]. When the flight can respond quickly to angle set and can follow the flight steadily, the attitude control debugging is successful. PID parameters of attitude control are shown in Table 2.

5.3. Fixed point and hover debugging
The position-type cascade PID controller is adopted for fixed-point and hover debugging after the aircraft is stabilized through attitude debugging and altitude debugging. And the aircraft needs to respond quickly to track the ground. When $K_p$ value is increased and $K_i$ value is decreased, the aircraft can track the ground track quickly. The aircraft can hover stably in the air, the setting parameters are recorded as shown in Table 3.
Table 2. Cascade PID parameters of attitude control

| The outer ring | The inner ring |
|----------------|----------------|
| P I D P I D |
| Pitch          | 6.3 0.06 0.0 1.8 0.18 0.8 |
| Roll           | 5.3 0.02 0.0 1.9 0.06 0.8 |
| Yaw            | 5.3 0.0 0.0 1.8 0.0 0.1 |

Table 3. fixed point and Hover PID parameters

| The outer ring | The inner ring |
|----------------|----------------|
| P I D P I D |
| Velocity loop | 8.0 0.01 0.02 4.5 0.02 0.6 |
| Trajectory loop | 8.3 0.01 0.02 4.5 0.02 0.6 |

6. Conclusion
A four-rotor autonomous target-dropping aircraft is designed and made in this paper. Based on Euler's theorem, the mathematical model of navigation coordinate system and carrier coordinate system are established. And the control attitude algorithm of aircraft is analyzed. In terms of hardware, the flight control system circuit is designed, including the main control circuit, attitude measurement circuit, target control circuit and image processing circuit. In the other hand of software, the cascade PID algorithm for aircraft attitude control, flight height control algorithm, attitude solving algorithm and image acquisition and processing software are designed.

The experiment is carried out on the real object made in the experiment. The results show that: when the control of attitude and height of the aircraft were carried, the size of proportional $K_p$, integral $K_i$ and differential $K_d$ were adjusted successively, and the control of attitude as well as height were successfully realized. And the positioning and hovering of the aircraft are also debugged. The value of $K_p$ and $K_i$ are adjusted as required. And the aircraft can quickly track the ground track and accurately complete the flight mission. The algorithm is validated to be correct by all of these pieces of evidences.

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